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"ESTABLISHMENT OF AN INSTITUTE FOR FUSION STUDIES"

Technical Progress Report

November 1, 1993 - October 31, 1994

**Richard D. Hazeltine, Director
Institute for Fusion Studies
The University of Texas at Austin
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July 1994

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OVERVIEW

The Institute for Fusion Studies is a national center for theoretical fusion plasma physics research. Its purposes are: (1) to conduct research on theoretical questions concerning the achievement of controlled fusion energy by means of magnetic confinement—including both fundamental problems of long-range significance, as well as shorter-term issues; (2) to serve as a national and international center for information exchange by hosting exchange visits, conferences, and workshops; (3) and to train students and postdoctoral research personnel for the fusion energy program and plasma physics research areas.

The theoretical research results obtained by the Institute contribute to the progress of nuclear fusion research, whose goal is the development of fusion power as a basic energy source. Close collaborative relationships have been developed with other university and national laboratory fusion groups, both in the US and abroad. In addition to its primary focus on mainstream fusion physics, the Institute is also involved with research in fusion-sidestream fields, such as advanced computing techniques, nonlinear dynamics, space plasmas and astrophysics, statistical mechanics, fluid dynamics, and accelerator physics.

The diversity of the research performed at the Institute is reflected in the list of recent IFS publications, given in the third section of this report. Last year IFS scientists published 73 scientific articles in technical journals and monographs. Also, three major review papers were written: “Quasi-Two-Dimensional Dynamics of Plasmas and Fluids” by W. Horton and A. Hasegawa (published in the new journal *Chaos*); “Solitary Waves and Homoclinic Orbits” by N. J. Balmforth (to be published in *Annual Reviews of Fluid Mechanics*); and “Hamiltonian Description

of the Ideal Fluid" by P. J. Morrison (to be published in the Proceedings of the Geophysical Fluid Dynamics Summer Program, Woods Hole Oceanographic Institution). Also, three books were published: *G. I. Budker: Reflections and Remembrances*, edited by B. N. Breizman and J. W. Van Dam (AIP Press, New York, 1994, 364 pages); *U.S.-Japan Workshop on Ion Temperature Gradient-Driven Turbulent Transport*, edited by W. Horton, M. Wakatani, and A. Wootton (AIP Press, New York, 1994, 592 pages); and *Chaotic Dynamics and Transport in Fluids and Plasmas*, edited by W. Horton, Y. Ichikawa, I. Prigogine, and G. Zaslavsky (American Institute of Physics, New York, 1993, 448 pages). Another book is scheduled to be published soon: *Physics of High Energy Particles in Toroidal Systems*, edited by T. Tajima and M. Okamoto (AIP Press).

The work of IFS scientists continued to receive national and international recognition. At the 1993 APS Division of Plasma Physics Meeting, invited papers were presented by P. J. Morrison on "The Energy of Perturbations for Vlasov Plasmas," P. N. Yushmanov on "Shear Flow Generation from the Neoclassical and Drift Wave Turbulence Effects," and J. B. Taylor on "Filamentation, Current Profiles, and Transport in a Tokamak." At the 1994 International Sherwood Controlled Fusion Theory Conference, an invited paper on "Effect of a Non-Uniform Resistive Wall on the Stability of Tokamak Plasmas" was presented by R. Fitzpatrick. At the upcoming 15th IAEA International Conference on Plasma Physics and Controlled Nuclear Fusion Research, IFS scientists will be involved in four invited papers. A number of invited talks were also given during the past year at various other conferences and workshops.

The Institute actively sponsors collaborative research programs with laboratories and universities throughout the US and the world. This past year, the IFS hosted 32 short-term visitors and 8 long-term (i.e., one month or more) visitors. A complete list of visitors is appended to this report. On behalf of the Department of Energy, the IFS also organizes the exchange activities of the US.-Japan Joint Institute for Fusion Theory and is their principal site in the United States. Last year this program sponsored two workshops in the US and two in Japan, four exchange scientist visits, and 12 joint computational projects. The IFS has also continued to be active in the US-Russian Federation exchange program.

A few specific examples may be cited of collaborations in which the IFS is involved. The Joint Program in Edge Physics, which was established by the IFS, facilitates collaborations with MIT and Culham on the theoretical physics of tokamak divertors. Also, the work of several IFS scientists on developing and applying sophisticated computational codes to simulate tokamak behavior is integrated into the "grand-challenge" Numerical Tokamak Project, a national collaborative effort among half a dozen research institutions, which is part of the federally-funded High Performance Computing and Communication Program. Also, two IFS scientists have recently spent extended periods visiting General Atomics to collaborate on alpha physics and MHD stability, respectively, and another IFS scientist is collaborating on-site at PPPL to analyze the resistive wall stability of the planned TPX tokamak.

In addition to its research activities, the IFS has an important educational function. This past year 15 graduate students worked on fusion and plasma physics thesis-degree projects under the supervision of senior IFS scientists, several of whom also teach courses in the Physics Department. Two of these students graduated with Ph.D. degrees last year. As part of its educational role, the Institute also has a postdoctoral training program, which involved five postdoctoral fellows last year.

IFS scientists are also active in various forms of service to the scientific community. A number of these may be listed: associate editor for *Reviews of Modern Physics*; member of the ITER U.S. Steering Committee; chairman of the US Theory Coordinating Committee; chairman of the PPPL Theory Advisory Board; chairman of the MIT Plasma Fusion Center Theory Advisory Board; chairman of the ITER Subgroup on Divertor Simulation; member of the USDOE Edge Physics Working Group; member of the Sherwood Conference Steering Committee; member of the TPX Program Advisory Committee; ITER liaison for the TTF Fast Particle Working Group; member of the ITER Expert Group on Energetic Particles, Heating, and Current Drive; member of the Steering Committee for the Numerical Tokamak Project; member of the Advisory and Program Committees of the 1994 International Conference on Plasma Physics. An IFS scientist serves as the director of the plasma physics group at the International Centre for Theoretical Physics (Trieste, Italy). Recent testimony before the US House of Representatives Energy and Water Development Subcommittee, entitled "Fusion Energy and Fundamental Research" (by R. D. Hazeltine), will appear in *The Congressional Record*. Also, IFS scientists were the organizers for several meetings, including the 1994 Sherwood Fusion Theory Conference (Dallas), the US-Japan Workshop on High-Energy Particles in Toroidal Systems (Irvine), and the TTF Specialists' Meeting on Codes for Simulating Collective Alpha Particle Effects (St. Louis).

TECHNICAL PROGRESS AND RESULTS

During FY 1994, a number of significant scientific advances were achieved at the IFS, both in long-range fundamental problems as well as in near-term strategic issues, consistent with the Institute's mandate. Examples of these achievements include, for example, tokamak edge physics, analytical and computational studies of ion-temperature-gradient-driven turbulent transport, alpha-particle-excited toroidal Alfvén eigenmode nonlinear behavior, sophisticated simulations for the Numerical Tokamak Project, and a variety of non-tokamak and non-fusion basic plasma physics ideas. Many of these projects were done in collaboration with scientists from other institutions. Important research discoveries are briefly described in what follows.

Tokamak fluid dynamics

The study of macroscopic instabilities has acquired a special urgency in the context of designing the next generation of tokamak devices. Internal and external kink modes, in particular, present a threat to the successful operation of these devices. Conversely, control of these modes extends hope for improving tokamak performance. Guided by recent experimental results, IFS has made key contributions to recent advances in the understanding of both types of kinks.

Filamentation, current profiles, and transport in a tokamak—The well-known theory of plasma relaxation, in which a turbulent magnetized plasma reaches a state of minimum energy subject only to constant magnetic helicity, has been successful in predicting or interpreting the magnetic field profiles and other features of many confinement experiments (e.g., the toroidal pinch, spheromak, and multipinch)—but not the tokamak. This is presumably because only at a disruption does a tokamak plasma experience the strong turbulence that leads to the relaxed state. Nevertheless, even, though it does not fully relax, a tokamak plasma does appear to have a tendency toward a preferred natural profile. This tendency is often called “profile consistency.” A theory to account for this was recently developed at the IFS, in which the tokamak plasma is represented with a microscopically filamented current structure. The statistical mechanics of this filamentary model not only yields natural current profiles, but also predicts an anomalous inward-pinch of both heat and particles. These results compare well with experiments, since an inward particle flux has been observed in many tokamaks, and an inward flux of heat is often postulated in order to account for the behavior of certain tokamaks.

Rotational stabilization of ballooning modes—Sheared toroidal rotation has a significant stabilizing effect on ideal MHD ballooning modes. The effect of sheared toroidal rotation on the beta limit imposed by ideal MHD ballooning modes has been investigated in a collaboration between the IFS, General Atomics, and the University of Maryland. An s - a diagram has been obtained demonstrating and quantifying the stabilizing effect of rotation shear. A new technique for calculating the growth rates of the eigenmodes from the time-dependent solutions obtained with the ballooning representation has been developed and used to explain the resonances observed in the numerical simulations. The values predicted to be needed for significant stabilization either already exist or are experimentally attainable.

Nonlinear growth of strongly unstable tearing modes—This work focuses attention not on the sawtooth crash-time question, but rather on the more operationally important problem of determining the conditions for the onset of the crash. The evolution of the strongly unstable tearing modes responsible for major disruptions as well as the sawtooth crash was investigated. Two regimes of growth have been shown to occur, depending on the relative rate of current diffusion and flux reconnection. For very thin islands, the current evolves in diffusive quasi-equilibrium, and its evolution is ruled by Rutherford's law. As the island grows, the rate of reconnection increases and eventually overtakes the rate of current diffusion. At this point a

transition occurs to the mode of rapid reconnection characterized by helicity conservation.

Stability of coupled tearing and twisting modes in tokamaks—The highly tuned (in rotation frequency) nature of the response function of tearing and twisting parity layers to helical magnetic perturbations is found to effectively decouple all of the tearing and twisting modes in the plasma at low amplitude. Above a certain threshold amplitude (which can easily be evaluated) the uncoupled modes suddenly start to “lock” together and thereby become significantly more unstable. At high- n , unstable twisting parity modes (i.e., ballooning modes) can lock to tearing modes, giving rise to a configuration with interlocking magnetic islands on every second coupled rational surface.

Effect of a static external magnetic perturbation on resistive mode stability in tokamaks—The analysis of the stability of resistive modes in a tokamak plasma has been generalized to include the effect of error fields. The extended dispersion relation takes the form of an inhomogeneous square matrix equation. A general formalism for calculating the right-hand side in terms of the applied external perturbation has been developed and implemented in the T7 code. The model predicts that there is a threshold amplitude for externally driven reconnection. This result is in good agreement with experimental observations and have some disturbing ramifications for ITER. One aspect of the model that requires further work is the predicted steady-state island width driven by a field error after mode locking has occurred, since the experimental island widths are far larger than expected.

Effect of a non-uniform resistive wall on the stability of tokamak plasmas—The conventional, rather idealized, MHD theory of external kink stability was extended to take into account the cold halo plasma in the scrape-off region, as well as the effect of an incomplete stabilizing shell. With toroidal gaps, it is found that if the wall stability index exceeds a critical value, the flux becomes entirely concentrated in the gap regions, and the mode can then “explode” through the gaps with an ideal growth rate. This work is highly relevant to the design of ITER and TPX and, in general, to tokamaks with incomplete stabilizing shells. There are also ramifications for the design of MHD feedback systems, since an incomplete resistive wall is equivalent to a low-gain feedback system with finite coils.

Helical temperature perturbations associated with tearing modes in tokamaks—The flow of heat across a magnetic island was studied, in order to be able to determine the mode structure from electron cyclotron emission experimental data. The results show that there is a non-trivial threshold island width above which the local temperature profile is flattened and the island is strongly destabilized by the perturbed bootstrap current, and below which neither of these two effects occur. This may offer an explanation for the experimental inference that most tearing modes in tokamaks are intrinsically stable but can become extremely unstable if “pushed” slightly by an external field error. In an ongoing collaborative effort, the ECE groups (from Texas FRC and Auburn) operating on TEXT are working on ways to test this model experimentally.

Edge physics

The study of edge plasma physics is an area of growing attention, with particular relevance to topics such as L- to H-mode confinement transitions, divertor design for ITER and TPX, etc. Some IFS work in this area is being conducted collaboratively with scientists from MIT and Culham Laboratory through the Joint Program in Edge Physics.

Neutral plasma interaction—The dynamics of a hot plasma impinging on a colder neutral gas has been studied, with the idea of simulating divertor physics in ITER. This effort was extended to treat regimes in which the charge exchange mean-free-path is long. In particular, the charge-exchange viscosity in the TEXT tokamak was found to be orders of magnitude larger than the neoclassical value.

Divertor sheath physics—The scrape-off layer associated with a tokamak divertor or limiter at low collisionality, was analyzed by means of reducing the ion scrape-off model to a Wiener-Hopf problem. The resulting analytical expression yields a realistic 2-D kinetic description of the radial boundary layer and the electrostatic potential caused by a divertor (or a limiter). The electron problem is shown to involve two coupled diffusion processes ("double diffusion"), in radius and energy; its solution gives an expression for the radial electric field in the scrape-off layer.

Monte-Carlo study of orbits and transport with large electric fields—A Monte Carlo code was used to show that ion orbit geometry leads to poloidal variation in prompt ion losses. The resulting poloidal electric field acts self-consistently to reduce the poloidal asymmetry.

Neoclassical-turbulent transport model—A new description of the plasma transport was developed that treats the poloidal and toroidal flow velocities on equal footing with the plasma turbulence. The entire system conserves energy and momentum to within collisional dissipation and friction with the neutrals. Energy and momentum is transferred on time scales corresponding to tens of microseconds between the fluctuations and the mean shear flows. Application of this new system shows that abrupt transitions to new states of low turbulence and high flow velocities occur when the auxiliary power input exceeds a threshold value and the neoclassical viscosity and non-ambipolar losses are sufficiently weak. Above threshold the system goes into a series of relaxation oscillations, where transitions between the states of high turbulence/low flow velocities and low turbulence/high flow velocities occur at intervals on the order of milliseconds. The system thus allows predictions about profile relaxations to near-marginal states and the L-H transitions.

MARFEs in tokamak edge plasma—A 2-D nonlinear time-dependent fluid model was developed that elucidates the basic mechanism of multifaceted asymmetric radiation from the edge of tokamak plasmas. A mixed Eulerian-Lagrangian formalism was used to describe MARFE formation in terms of the formation of stable equilibrium patterns in a 2-D active reaction-diffusion system with nonlocal constraints.

Scrape-off layer and divertor transport—Among the candidates to explain the large turbulent fluctuations observed in the scrape-off layer and associated with SOL transport are end-wall impedance-driven instabilities and ionization-driven and impurity-radiation modified drift waves. The end-wall impedance-driven instability takes into account the coupling of the electron temperature fluctuation to the potential fluctuation through the parallel currents into the Debye sheath at the limiter or divertor plates. The scaling of the turbulent fluxes may be Bohm-like or between Bohm and gyro-Bohm, due to the absence of magnetic shear that provides radial location. Simulations and theory are being carried out in collaboration with LLNL. Also, the stability of plasma flow in the SOL was studied when surface sheath impedance and axial shear in the $E \times B$ flow is included; growth rates are found to be maximum for an insulating end plate, and mixing-length estimates of the diffusivity are comparable to experimental values.

Turbulence and transport

Understanding the physical processes that control particle, momentum, and energy transport in thermonuclear plasmas is of fundamental scientific interest and practical importance. Presently unresolved confinement physics issues are critically relevant to the ITER design and thus to any fusion power plant. A principal goal of IFS research is to obtain a sound understanding of the varied and competing transport mechanisms, and to produce reliable predictions for transport in specific geometry and plasma parameter regimes. In this effort, new algorithms and modeling tools for large-scale, self-consistent kinetic simulations have been developed by IFS scientists.

Marginal stability analyses—A comprehensive linear code that employs a unique and very fast implicit algorithm was used to analyze several L-mode discharges from TFTR. Although no assumptions were made about the relative importance of the various $E \times B$ instabilities, only toroidal ion temperature gradient modes were found to be unstable. Furthermore, inside about half the minor radius, the profiles were very close to marginal stability. Outside this radius, the profiles were progressively more unstable. It was shown that this progressive deviation from marginality could explain the observed radial increase of the thermal diffusivity.

ITG plasma transport in global toroidal geometry (and shear flow control)—The Toroidal Particle Code continued to be employed for nonlinear, toroidal, and global particle simulations of $E \times B$ microturbulence. As a consequence of the toroidicity-induced coupling of rational surfaces over many poloidal mode numbers, these simulations observed that the ion temperature gradient mode in toroidal plasmas exhibits the development of extended potential "streamers" localized to the outside of the torus, radially constant eigenfrequency, global temperature relaxation, and radially increasing ion heat conductivity. Also, a model of transport based on the marginally unstable critical temperature gradient has been proposed. Currently this code is being upgraded to include shear flow velocities.

Energy transport due to electron plasma waves—Several important physical effects have been found to greatly enhance the energy transport above the original Liu-Rosenbluth result. Magnetic shear introduces radial variation that can cause the transport step length to increase to become on the order of the tokamak minor radius. Magnetic field curvature has the effect of concentrating plasma transport in the direction of decreasing major radius, which might explain how electron energy is transported to the inner edge plasma for a “marfe” to occur at high plasma densities. The reduction of Landau damping at short distances from the emitting electrons also tends to increase the transport step length. Finally, transport can be enhanced due to the plasma current from a non-Maxwellian tail in the electron distribution function, and hence it is likely that electron plasma wave transport is the cause of neo-Alcator scaling in tokamaks. Interestingly, in reversed-field pinches, energy transport due to electron plasma waves can also be strong.

Comparison of linear codes for toroidal plasma instabilities—Scientists at IFS and PPPL collaborated to compare two completely independent codes that both solve the linearized gyrokinetic equation with the “s-a” model tokamak equilibrium and the ballooning formalism for high- n toroidal instabilities. One code implements an initial value calculation, on a grid, with a Lorentz collision operator, whereas the other implements an eigenvalue calculation, with basis functions, using a Krook collision operator. For the ion-temperature-gradient-driven drift mode, good agreement was obtained in an electrostatic test case and also in two TFTR L-mode experimental cases.

Electron thermal transport—Work on the electron thermal conductivity has continued by applying the stochastic diffusivity derived from test -particle electron diffusion, which is a strong function of local magnetic shear on the outside of the torus. The local shear decreases with increasing plasma beta-poloidal; this yields a plasma current scaling in the resulting energy confinement time.

Nonlinear orbit dynamics—A new method was developed for calculating the response functions, such as the linear susceptibility and conductivity, in the case of 2D equilibria with nonintegrable orbits. The simulation method is shown to reproduce the standard Vlasov formulas for integrable orbits with delta function resonances at the Doppler shifted cyclotron resonances. In the case of finite or large gyroradius particles with chaotic orbits, the resonances form continuous absorption bands with enhanced dissipation at low frequencies. These new results are very important for low frequency trapped particle modes and tearing modes. New studies of the accuracy of the nonlinear orbits are being carried out by a comparison of the computations for chaotic orbits and the associated diffusion coefficients obtained from a RIS6000 work station with those obtained from a CRAY 90 supercomputer.

Turbulence and coherent structures—The role of nonlinearly produced and sustained coherent structures in $E \times B$ turbulence continued to be studied. In particular, the competition of magnetic shear with nonlinear self-focusing, the stability properties of the self-organized nonlinear

structures as a function of their speed and size, the occurrence of nonlinear growth in linearly stable systems, the spectral indices of the wavenumber spectrum in regions below and above the characteristic dispersion scale length, and the degree of anisotropy at the wavenumber spectrum were investigated in detail. A new review article was written on drift wave turbulence, which describes the nature of the turbulent fluctuations versus the self-organization into coherent structures, specifically for the Charney-Hasegawa-Mima equation.

Isotope scaling of plasma confinement in tokamak devices—Despite the fundamental nature and widespread experimental observation of an ion mass dependence, theoretical explanations for the isotope scaling of the tokamak plasma energy confinement are rare. Moreover, conventional transport theories fail to predict the correct isotope scaling. Neoclassical theory, conventional ion pressure gradient driven turbulence models, and resistive ballooning theory, for instance, predict a degradation of confinement from hydrogen to deuterium and to tritium. New IFS studies of the toroidal ion temperature gradient driven mode of hydrogen, deuterium, or tritium plasmas containing impurity ions show a possible explanation. The maximum growth rate of the mode with respect to the poloidal mode number has a certain scaling with the effective ion mass number that is in reasonable agreement with experimental observations. This behavior provides a possible explanation of the isotope scaling of the confinement time if the radial correlation length of the turbulence is determined by the machine size.

Poloidal shear flow generation by parallel flow induced turbulence—It is well accepted that turbulence introduces anomalous particle and energy transport, causing deterioration in plasma confinement. However, it was recently discovered that turbulence may drive sheared poloidal plasma flow which, in turn, suppresses turbulence and improves plasma confinement. Parallel flow shear existing in tokamak plasmas is a free energy source that can drive turbulence and influence plasma confinement. The driving and suppression mechanisms for turbulence induced by parallel plasma flow shear was studied quasilinearly and nonlinearly. There is evidence that parallel velocity shear may introduce deterioration of plasma confinement when it is at a low level; however, it may drive poloidal velocity shear and lead to improvement of plasma confinement if it is strong enough.

Impurity transport in tokamaks—From a detailed analysis of impurity transport experiments on TEXT, it was concluded that $E \times B$ turbulent diffusivity in the strong turbulence regime can interpret the spectroscopically measured test particle transport coefficients produced by laser blow-off injection of trace amounts of scandium. Neoclassical and quasilinear estimates of the diffusivity provide poorer fits to the experimental data. Knowledge of the transport rates for impurities is both of fundamental interest and practical importance. The diamagnetic capabilities of the TEXT-U experiment are uniquely able to allow a direct comparison between experiment and theory because the HIBP diagnostic can measure the dependence of both the fluctuating and mean value of the electrostatic potential resolve in radius time.

Detailed experimental comparisons—Recent code simulations at the IFS may explain the L-mode, Supershot, PEP-mode, and VH-mode confinement regimes as consequences of ion temperature gradient mode transport. Parameterized forms for the ion and electron thermal diffusivity were derived and employed in a 1-D power balance code to predict temperature profiles, with actual experimental profiles used for other local parameters. Dozens of TFTR discharges have been simulated, and good agreement obtained over most of the minor radius. For example, the very low core thermal diffusivity of supershots appears to be explained primarily by the high ion-to-electron temperature ratio (strongly stabilizing), carbon impurity dynamics, beam density dilution, and finite-beta stabilization.

Monte-Carlo interpretation of low-noise particle simulations—The relationship between well-known, long-standing Monte Carlo techniques and the various so-called δf low-noise particle simulation algorithm was explained in a lucid way that makes clear why the δf algorithm, which was pioneered at the IFS, has almost replaced full particle algorithms for fusion transport applications. The Monte Carlo variance reduction methods are then applied to linear and nonlinear studies of pure electron plasmas, the low-noise techniques making it possible to follow the linear evolution and saturation of even very weakly unstable resonant diocotron modes.

Alpha particle physics

The physics of alpha particles, especially their collective interaction with Alfvén waves in burning plasmas, has assumed great importance in connection with the deuterium-tritium experiments being performed currently on the TFTR tokamak and with the design effort for the ITER device. Some of the IFS work on these issues is being carried out through inter-institutional collaborations with JET and General Atomics and through the TTF Fast Particle Working Group.

Stability of Alfvén waves in ignited plasmas—Fundamental studies were continued of the linear stability of toroidal Alfvén eigenmodes (TAE) and associated modes, e.g., the kinetic TAE. A theory of poloidal harmonic coupling was developed for arbitrary mode numbers. An examination of finite-beta effects on TAE stability and mode properties is now underway.

Nonlinear Alfvén Wave-Alpha Particle Dynamics—An analytical model and a numerical procedure have been developed that give a self-consistent, first-principles kinetic nonlinear description of Alfvén wave instabilities driven by energetic particles in a plasma. The nonlinear steady-state saturation and bursting scenarios predicted from analytical theory were confirmed by numerical simulations involving resonant particles and wave trapping. This allows interpretation of the bursts in wave energy and fast particle losses that have been observed in tokamak experiments with high-energy neutron beam injection.

Harmonic cyclotron emission induced by fast ions—A novel mechanism of two-streaming in gyrospace was proposed that can lead to a cyclotron instability in real space, for which fast ions drive electrostatic ion Bernstein waves unstable. This mechanism may perhaps be a candidate to explain the ion cyclotron emission observed at low harmonics in deuterium-deuterium and deuterium-tritium experiments in the JET experiments. Also, particle-in-cell simulations show that the two-gyro-stream instability can excite a novel anomalous process causing the perpendicular energy of fast ions to be thermalized and lost on average to bulk ion heating, instead of slowing down classically and losing their energy to bulk electrons, which would have significant implications for sustaining fusion ignition.

Continuum damping of ideal toroidal Alfvén eigenmodes—A ballooning representation approach is utilized in order to calculate the continuum damping on TAE modes, which can be strongly excited by alpha particles in ignited tokamak plasmas. By analogy to the Fermi golden rule for decaying systems in quantum mechanics, the damping rate can be expressed explicitly in terms of the coupling of the TAE mode to the continuum spectrum.

Basic plasma physics

Symplectic maps for magnetostatics and Hamiltonian mechanics—Various methods were investigated for constructing 2-D area-preserving maps for general Hamiltonian systems. One of these methods was used to obtain an integrable Poincaré map for the field lines in a tokamak with a single-null divertor and arbitrary safety factor profile. Adding a small perturbation to the divertor map will allow exploration of the properties of an ergodic limiter.

Infinite dimensional noncanonical Hamiltonian system—The well-known Vlasov-Poisson system of equations for waves in a plasma is an example of an infinite dimensional noncanonical Hamiltonian system. This system was first linearized about a stable homogeneous equilibrium, and then diagonalized by the use of canonical variables and the introduction of a coordinate transformation that brings it into action-angle form. The procedure is non-trivial because the Vlasov Poisson system has a continuous spectrum.

Energy of perturbations for Vlasov plasmas—The usual expression for the dielectric wave energy of electrostatic perturbations about homogeneous equilibria is deficient because resonant particles are not properly treated. A linear integral transform (equivalent to a change to normal coordinates in an infinite dimensional Hamiltonian system) is derived that correctly incorporates the energy content of resonant particles.

Advanced Ideas and Interdisciplinary research

Particle diffusion from beam-beam interaction in a synchrotron collider—Beam-beam interactions are one of the principal limitations on beam intensity in synchrotron colliders. Slow particle diffusion in phase space away from tune resonances in large hadron colliders was therefore examined with the use of a new δf code. Computations show that all particles are diffusive after 10^5 rotations, in contrast to previous single-particle tracking results. Moreover, the diffusion coefficients are several orders of magnitude higher than the tracking code results.

Laser wakefield excitation—IFS scientists are collaborating on theoretical and experimental studies of wakefield excitation by table-top terrawatt lasers, for which the spatio-temporally resolved wakefield structure can be measured on the femtosecond time scale. In a different but related collaboration, the acceleration of electrons in a strongly nonlinearly enhanced electric field was analyzed, leading to the discovery of ionizational wakefield excitation, 2-D “auroral arc” enhancement effect, and the increase of the photon group velocity in an active medium.

Magnetically constricted intergalactic plasmas—The presence of global cosmic magnetic fields was shown to be a possible mechanism for the origin of cosmic X-ray background radiation. The so-called ABC dynamo model was used to obtain the cellular morphology of magnetic fields in the expanding universe.

Magnetless magnetic fusion—A concept for a thermonuclear fusion reactor was proposed in which the plasma pressure is balanced by direct gas/wall interaction in a high-pressure vessel, with energy confinement achieved by means of the self-contained toroidal magnetic field sustained either by external current drive or charged fusion products. This main advantage of this scheme is the absence of large external magnetics, leading to a cheaper design and reduced energy consumption.

Neural net forecasting of tokamak disruptions—The neural network is a general adaptive algorithm that can learn from previous data and predict future trends without the programmer's understanding of specific details of the nature of the data. IFS scientists used the perceptron-type neural net algorithm, with one or more hidden layers with back propagation, and trained the network from experimental time series data of the poloidal magnetic field time derivative and X-ray emission from the TEXT tokamak. Some success was attained in predicting disruptions a msec prior to the events.

Limiter end loss with finite gyroradius—A method was created for analyzing the stability of flute modes in a two-energy-component plasma that is terminated by a conducting limiter. This can be applied to investigate end loss in open-ended mirror machines for which large Larmor radius effects are significant.

Toroidally-linked mirror machine as a neutron source—Because it is compact and can produce high-beta plasmas, a mirror machine may be ideal as a neutron source for materials testing

purposes. The overall efficiency of a neutron source is determined by the electron temperature, which is typically low compared to the ion temperature, due to rapid end loss in a linear mirror. Therefore a system of quadrupole mirrors linked by simple toroidal cells with elliptical cross-section was proposed, in a collaboration between the IFS and the Kurchatov Institute. It was shown that plasma flow due to radial electric fields plays the role of rotational transform. Finite pressure equilibrium solutions can be attained for beta values of up to 10%. Ideal ballooning stability in one of the toroidal sections limits the beta to less than 1%, although kinetic effects are stabilizing. A transport model shows that the system in steady state maintains high beta in the minimum-B trapping regions and low beta in the toroidal regions.

Decay of magnetic helicity producing polarized Alfvén waves—The damping of a circularly polarized Alfvén wave can drive current in a background plasma. Here the inverse process was shown to hold, viz., a decay of mean-field helicity that produces circularly polarized Alfvén waves. A fast, super-Alfvénic electron beam propagating along an ambient magnetic field and carrying net current can be the free energy source for this spontaneous conversion of plasma helicity to wave helicity. Because the background helicity induces a frequency shift in the eigenmodes, it becomes possible for a sub-Alfvénic electron beam to excite a nonsingular Alfvén mode.

Localized structures in an electron-positron ion plasmas—The presence of a small fraction of ions in electron-positron plasmas is shown to allow the formation of stable, localized structures with relativistically strong amplitudes of electromagnetic radiation and large density bunching. These stable solutions may explain micropulsations in pulsar radiation and may also explain structure formation in the early universe.

IFS PUBLICATIONS DURING FY 94

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BENKADDA, Sadruddin	I.M.T., Marseille, France	March 16-18, 1994
BETTI, Ricardo	University of Rochester	July 1-August 15, 1994
BUSBY, Lee	Lawrence Livermore National Lab	May 3, 1994
CHOQUET-BRUHAT, Yvonne	University of Paris	Nov. 15-Dec. 15, 1993
CONNOR, Jack	Culham Laboratory	March 16-18, 1994
DEBENHAM, Phil	DOE, Washington	April 6, 1994
DENDY, Richard	Culham Laboratory	February 26-28, 1994
FIALA, Vladimir	Univ. of Minnesota	April 26-28, 1994
HOJO, H.	University of Tsukuba, Japan	March 5-8, 1994
ICHIMARU, Setsuo	Tokyo University, Japan	February 13-16, 1994
JUNGWIRTH, Karel	Czech Academy of Sciences	June 28-30, 1994
KAISIG, Michael	Univ. Wurzburg, Germany	August 27-October 8, 1993
KISHIMOTO, Yasuaki	J.A.E.R.I., Japan	September 1-3, 1993
KOMORI, Akio, et al.(+5)	NIFS, Nagoya-Japan	March 10, 1994
KONDOH, Yoshiomi	Gunma University-Japan	July 26-October 25, 1994
KUZNETSOV, Evgenii	Univ Arizona & Landau Institute, Russia	May 21-25, 1994
MAKASHIMA, K.	Univ. of Tokyo	January 15-17, 1994
MATSUMOTO, Ryoji	Chiba University, Japan	Feb. 24-March 23, 1994
MATSUMOTO, Ryoji	Chiba University	Sept. 1-October 1, 1994

IFS VISITORS - 1993-94

Name	Institution	Dates of Visit
MEERSON, Baruch	Hebrew University, Jerusalem	Aug. 13,-Sept. 28, 1993
MILLER, Robert	General Atomics	March 16-17, 1994
NAKAJIMA, K.	KEK, Japan	March 20-27, 1994
NEILSON, Hutch	Princeton PPL	January 11, 1994
PASTUKHOV, Vladimir	Kurchatov Institute	March 18-April 1, 1994
PERKINS, John	Lawrence Livermore National Lab	February 7, 1994
PORCELLI, Franco	JET-United Kingdom	March 16-19, 1994
SERGEEV, Alexander	Inst. Appl. Phys., Gorky,Russia	Jan. 28-Feb. 23, 1994
SHIBATA, Kazunari	National Astro. Obs., Tokyo	August 1-September 1, 1994
SHVETS, Genady	Massachusetts Inst. of Technology	June 2, 1994
SMOLYAKOV, A.I.	University of Saskatchewan	March 18-21, 1994
SOBEHART, Jorge	Los Alamos National Lab	October 4, 1993
SUGIYAMA, Linda	MIT Plasma Fusion Center	March 18-21, 1994
TANAKA, Motohiko	NIFS, Nagoya-Japan	May 17-21, 1994
TATARONIS, John	University of Wisconsin	September 17-20, 1993
THYAGARAJA, A.	Culham Laboratory	October 3-29, 1993
TOKUDA, S.	Plasma Theory Lab, JAERI	March 23-25, 1994
VEDENOV, Alexander	Russia	September 27-29, 1993
VEKSTEIN, Gregory	University of St. Andrews, Scotland	September 6-9, 1993

IFS VISITORS - 1993-94

Name	Institution	Dates of Visit
VEKSTEIN, Gregory	Univ of St. Andrews, Scotland	~ August 1, 1994 (for 1 wk)
WOLFE, David	Los Alamos National Laboratory	June 13-21, 1994
YAGI, Masatoshi	J.A.E.R.I., Japan	Sept. 1, 1993-June 1, 1994
YOSHIDA, Zensho	University of Tokyo	September 8-30, 1993
ZABUSKY, Norman	Rutgers University	March 9, 1994

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