"ESTABLISHMENT OF AN INSTITUTE FOR FUSION STUDIES"

Final Technical Report

June 1, 1980 — March 1, 1998

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OVERVIEW

The mission of the Institute for Fusion Studies has been to serve as a national center for theoretical fusion and plasma physics research. As an independent scientific group of critical size, its objectives were to conduct research on fundamental phenomena important to fusion; to serve as a center for fusion theory exchange activities with other countries; to exchange scientific developments with other academic disciplines; and to train students and postdoctoral fellows in fusion and plasma physics research.

The theoretical results obtained at the Institute have contributed to the progress of research in plasma science and to the development of fusion power as a basic energy source. As part of its focus on fusion and plasma physics, the Institute has also been involved with research in numerous related fields, such as fluid dynamics, space plasmas and astrophysics, plasma-based particle accelerators, advanced computation, semiconductor plasmas, statistical mechanics, and plasma processing.

Scientific Publications

The diversity of the research that has been performed at the Institute is well reflected in its scientific publications. During the 18-year period covered by this final technical report, IFS scientists have published 1,002 scientific articles in technical journals and monographs. Among these were 18 review papers that provided systematic, integrated overviews of certain key research areas. (Complete bibliographies of published papers have been previously provided to DOE in the Institute's annual reports; the list of papers published during the last twelve months is attached at the end of this report.)

In addition, IFS scientists published 17 books. The most recent examples are two advanced textbooks, which have garnered critical praise, one entitled *Plasma Astrophysics* and the other entitled *The Framework of Plasma Physics* (both published by Addison-Wesley).

Research done at the IFS has often been spotlighted in the popular press. Some recent instances are the following. Theoretical predictions from the IFS-PPPL transport code concerning ITER performance were reported in *Science* magazine (6 December 1996, vol. 274, pp. 1600-1602), and this article was then extensively publicized by CNN News, CBS News, Associated Press, *Business Week*, and various newspapers (e.g., *The New York Times*, 10 December 1996, p. B11). A symposium organized by an IFS scientist on short-pulse laser accelerators was featured in an article in *Science* (5 January 1996, vol. 271, pp. 25-26). Results presented at a workshop organized by an IFS scientist on "Interactions of High-Power Waves with Plasmas and Matter" were described in *Science* (vol. 275, 24 January 1997, pp. 481-482). IFS research on using ultra-intense lasers to mimic the radiation in the vicinity of a black hole was mentioned in a *Science* article about "laboratory astrophysics" (18 April 1997, vol. 276, pp. 351-353). The work of an IFS scientist on the laboratory reproduction of astrophysical plasma conditions by means of short-pulse, ultrahigh-intensity lasers was featured in an article in *Air & Space Smithsonian Magazine* and also in an overview article in *Physics Today* (January 1998, p. 22).

Invited Conference Presentations and Honors

The work of IFS scientists has consistently received national and international recognition. To mention a few recent examples: At the 1997 Division of Plasma Physics Meeting of the American Physical Society, an invited paper was presented by W. Dorland on "Neoclassical spherical tokamaks." At the 1998 International Sherwood Controlled Fusion Theory Conference, invited papers were presented by J. Candy on "Spontaneous hole-clump pair creation in a weakly unstable plasma" and by R. Fitzpatrick on "Bifurcated states of a rotating tokamak plasma in the presence of a static error-field." At the 1998 DOE Transport Task Force Meeting, an invited paper was presented by B. Breizman on "Near-threshold kinetic instabilities and fast particle transport: Observations and interpretation." The same paper was selected for an oral talk at the 1998 International Conference on Plasma Physics, combined with the European Physical Society Meeting. Four papers with IFS scientists as lead authors were selected for presentation at the 1998 IAEA International Conference on Controlled Nuclear Fusion Research: "Attaining neoclassical transport in ignited tokamaks" by M. Kotschenreuther et al.; "Collective phenomena with energetic particles in fusion plasmas" by B. Breizman et al.; and "Intrinsically steady-state tokamaks" by K. Shaing et al. Numerous other invited talks were also given by IFS scientists at various conferences, summer schools, and workshops, both in the US and abroad.

Other noteworthy honors included the Ernst Mach Honorary Medal for Merit in the Physical Sciences, which was awarded in 1998 by the Academy of Sciences of the Czech Republic to an IFS scientist, B. Breizman, in honor of his scientific research achievements. Also in 1998 the U.S. Department of Energy awarded a two-year grant in its Plasma Physics Junior Faculty Development Program to R. Fitzpatrick, an IFS scientist and assistant professor in the Department of Physics.

National and International Collaborations

The Institute has actively sponsored collaborative research programs with laboratories and universities in the US and throughout the world. During the past 18 years, the IFS hosted 167 long-term visitors (i.e., three weeks or more) and 497 short-term visitors.

On behalf of the US Department of Energy, the IFS has also administered the exchange activities of the US.-Japan Joint Institute for Fusion Theory and served as their principal site in the United States. Cumulatively this international program has sponsored 57 workshops in the US and Japan, 90 exchange scientist visits, and 77 joint computational projects.

A few recent specific examples may be cited of scientific collaborations in which the IFS has been involved. Several IFS scientists have worked to develop and apply sophisticated computational codes for simulating tokamak behavior as part of the "grand-challenge" Numerical Turbulent Tokamak Project, a national consortium involving six national laboratories, five universities, and three advanced computing centers. These same codes have been compared and benchmarked through the DOE Cyclone Working Group. The IFS helped establish the Joint Program in Divertor Physics, which organizes collaborations among scientists at IFS, Massachusetts Institute of Technology (MIT), and UKAEA Culham Laboratory on the theoretical physics of tokamak edge plasmas. IFS theorists have actively collaborated with colleagues at the Princeton Plasma Physics Laboratory (PPPL) on developing and applying numerical simulations of transport to explain and predict tokamak confinement. In collaborations with PPPL, the Japan Atomic Energy Research Institute (JAERI), MIT, and the JET Joint Undertaking, IFS scientists have applied the nonlinear dynamics of energetic particles to explain results from NBI and ICRH experiments on JT-60U and the deuterium-tritium experiments on TFTR and JET. Various IFS scientists made extended visits (to mention only a few): to Sandia National Laboratory to study coalescence of multi-wire plasmas in Z-pinch assembly phase; to General Atomics in order to calculate tearing mode stability parameters for DIII-D discharges; to Tokyo University, National Institute for Fusion Studies, and the Japanese Institute for Advanced Studies as a visiting professor for research collaborations; to PPPL in order to investigate transport and equilibrium issues for the National Spherical Torus Experiment; to CEA Cadarache for transport studies on Tore Supra; and to JAERI to continue research on plasma wake-field accelerators.

The IFS has locally hosted approximately 15 workshops. Recently it hosted a workshop on *Frequency Sweeping Phenomena in Plasmas* (January 7-9, 1998, Austin, Texas), which involved about 25 theorists and experimentalists (including international participants) in an effort to find a common explanation for frequency chirping effects in plasmas, caused by resonant wave-particle interactions.

An IFS scientist has served for a number of years as the permanent organizer for the annual School on Plasma Physics that is held at the Abdus Salam International Centre for Theoretical Physics (Trieste, Italy).

Educational Role

Being sited at a university, the IFS combines the advantages of an academic setting with the perspective of a national laboratory group. During the 18 years of this grant, 55 graduate students worked on fusion and plasma physics thesis projects under the guidance of senior IFS scientists and graduated with Ph.D. degrees.

As part of its educational function, the Institute also has a postdoctoral training program. So far, 53 postdoctoral research fellows have worked at the IFS.

IFS scientists have supervised a number of students who came from other universities during the summer supported by DOE Undergraduate Research Fellowships. In 1997, for example, IFS scientists supervised an undergraduate student from Princeton University, the results of whose summer work were presented at the 1997 APS/DPP Meeting in the fall and subsequently written up for publication.

It is of interest to note that an undergraduate student who had previously worked at the IFS was awarded a prestigious Hertz Foundation Fellowship, as well as an NSF Fellowship, when he graduated from The University of Texas. He was supervised by IFS scientists during the summer of 1996 under a DOE Undergraduate Research Fellowship, and then was supported by the IFS for another half year to continue his work on software development for distributed computing, with application to numerical simulations of nonlinear TAE studies. These results were presented at the 1998 Sherwood International

Fusion Theory Conference in a poster on which he was co-author.

Leadership and Service

IFS scientists have been active in various forms of service to the scientific community. Examples are: chair of the Theory Coordinating Committee, Fusion Energy Sciences (US Dept. of Energy); member of the Program Advisory Committee, Princeton Plasma Physics Laboratory; member of the Program Committee for the Division of Plasma Physics of the European Physical Society; member of the Board of Physics and Astronomy and also member of the Plasma Science Committee, National Research Council (National Academy of Science); member of the Fusion Energy Sciences Advisory Committee (US Dept. of Energy); member of the ITER Steering Committee, US Home Team; leader of the Joint Program in Divertor Physics; member of the Program Advisory Committee, Plasma Fusion Center, MIT; member of the Advisory Board, International Conference on Plasma Physics; member of the ITER Expert Group on Alpha Particles, Heating and Current Drive; chairman of the Working Group on Fast Particle Physics of the US Department of Energy's Transport Task Force; member of the Scientific Committee for the Joint Varenna-Lausanne International Workshop on Theory of Fusion Plasmas; member of the International Organizing Committee for the Asia-Pacific Plasma Theory Conference; member of the DOE Panel on Measurement Needs in Magnetic Fusion Plasmas; member of the DOE *ad hoc* Working Group on International Collaborations; member of the organizing committee for the Forum on Major Next-Step Magnetic Experiments and organizer of the Physics Issues session; member of the DOE Review Panel for Computational Scientific Initiative on Nonlinear Complex Phenomena; member of the joint NSF/DOE panel for review of Basic Plasma Physics proposals; adjunct professor, Department of Space Physics and Astronomy, Rice University; correspondent for *Comments on Plasma Physics and Controlled Fusion*; member of the UNESCO Conference on Science and Technology; member of the DOE review committee for the General Atomics theory program.

IFS scientists have had leadership roles in the American Physical Society: viz., past chairman of the Division of Plasma Physics; member of the 1997 Selection Committee for the Award for Excellence in Plasma Physics Research of the American Physical Society; member of the Program Committee for the Division of Plasma Physics 1997 annual meeting; chair of the Committee for Distinguished Lecture Program in Plasma Physics (APS/DPP). Also, an IFS scientist was the organizer for the Alpha Particle Physics Forum at the 1997 APS DPP Meeting.

In other community service, the IFS director and associate director have served as the US chairman and executive secretary, respectively, of the steering committee for the Joint

Institute for Fusion Theory international exchange program with Japan. Also, several IFS scientists have participated annually in the Fusion Education Day in Washington, D.C.

TECHNICAL PROGRESS AND RESULTS

Numerous significant scientific advances have been achieved at the IFS, both concerning long-range fundamental problems, as well as near-term strategic issues, consistent with the Institute's mandate. Many of these projects were done in collaboration with scientists from other institutions.

Descriptions of these scientific achievements have been previously given in the Institute's annual DOE reports. In what follows, we confine ourselves to research done during the last twelve months. Some outstanding examples of technical achievements during this period include: interpretations for transport in reversed-shear tokamaks, 100% bootstrap-current-driven steady-state tokamak equilibria, refined predictions of ITER confinement performance, experimental interpretations based on nonlinear TAE wave-particle resonance features, cluster plasmas, error-field-driven magnetic reconnection, and stability condition for the Rayleigh equation.

Turbulence and transport

Understanding the physical processes that control particle, momentum, and energy transport in high-temperature laboratory plasmas is of fundamental scientific interest and practical importance. Confinement issues are critically relevant to the design of any fusion power plant. There has also been much interest in pursuing the enhanced confinement properties of advanced tokamak operational regimes. A principal goal of IFS research has been to obtain a sound understanding of the varied and competing transport physics mechanisms and to produce reliable predictions for transport in specific geometry and plasma parameter regimes. Part of this effort has involved the development of new algorithms and modeling tools for large-scale, self-consistent kinetic simulations.

Intrinsically steady-state tokamak plasma equilibria—Traditionally, tokamaks have been thought to require external current drive, either inductive or non-inductive, in order to maintain the plasma equilibrium. Even tokamaks with very large bootstrap current fractions ($\geq 90\%$) still require a small amount of seed current in the region near the magnetic axis. Recently, however, it was found that because trapped particles near the axis have potato-shaped orbits (not the usual banana orbits), the fraction of trapped particles does not vanish at the axis. Consequently they can drive a self-generated current near the axis. For typical tokamaks, the potato bootstrap current is in fact a significant fraction of the banana bootstrap current. Hence tokamak equilibria with only bootstrap current and diamagnetic current are possible. The existence of such equilibria was proved. This important result implies that tokamaks can have steady-state confinement performance, like stellarators.

Theory of enhanced reversed shear mode in tokamaks—Theory for H-mode improved confinement (observed in the edge region of tokamaks and stellarators) was extended to explain the improved confinement of the enhanced reversed shear mode (observed in the core region). It was found that toroidal magnetic field ripple-induced particle flux can cause the poloidal E×B velocity to bifurcate over the local maximum of the nonlinear poloidal (or parallel) viscosity. This mechanism, together with turbulence suppression due to the radial gradient of the E×B and diamagnetic velocity, can explain the enhanced reversed shear mode.

Ion transport near the tokamak magnetic axis—Conventional neoclassical transport theory does not hold near the magnetic axis, where orbital variation of the minor radius and the poloidal field significantly change the nature of ion guiding-center trajectories. The near-axis "potato" orbits are radially much wider than conventional tokamak banana-shaped orbits. This effect can lead to dramatic modifications of the plasma transport. In particular, it was shown that there is a plateau regime for the near-axis case. The ion thermal conductivity corresponding to this "potato-plateau" was calculated and found to be reduced through the orbit squeezing factor.

Transport without collisions—Traditional transport theory provides a closure of fluid equations that is valid in the collisional, short-mean-free-path limit. The possibility of extending an analogous closure to long-mean-free-path was examined. An appropriate kinetic equation, using a model collision operator, was solved rigorously for arbitrary collisionality, but weak Maxwellian source terms. The corresponding particle and heat flows were then expressed in terms of the density and temperature profiles. The transport matrix was found to be symmetric even at vanishing collision frequency; in the collisionless limit it takes the form of non-local operators. However, particle diffusion, which turns out to satisfy a local Fick's law for any finite collision frequency, becomes singular at vanishing collisionality, where the pressure gradient vanishes. The conclusion was that the fluxes can generally be expressed in terms of particle and energy sources, but not always in terms of pressure and temperature profiles.

Neoclassical profiles and advanced tokamak operation—The compatibility of neoclassical transport with MHD stability and steady-state high-beta tokamak operation has been investigated. Steady-state configurations (for D-T plasmas) have been identified that have less than 1% externally supplied current, volume-average beta of 50%, and excellent microstability properties. These calculations can be extended to include impurity and helium ash transport. The new NSTX experiment may provide a good test of theoretical predictions that favor a compact ($R \cong 1$ m), low-aspect-ratio, low-power ($\cong$30 MW) ignition experiment.

Transport matrix for advanced tokamak confinement regimes—In the regimes for advanced tokamak confinement, the values of both the radial electric field and the radial electric field gradient are large. The appropriate transport coefficients for these regimes were derived and found to be significantly modified. This theory can be applied to model the process of ion heat transport in advanced tokamaks.

Transport processes close to the magnetic axis in tokamaks and quasi-helically symmetric stellarators—In order to model the plasma performance in these devices, analytic formulas for the transport coefficients and especially for the bootstrap current were developed by studying the asymptotic limits of the transport fluxes in various collisionality regimes in the near-axis region. The bootstrap current formula can be used to model the cold start-up process in intrinsically steady-state tokamaks.

Symmetries and neoclassical transport theory—Advances were made in the current understanding of the theoretical structure of the Onsager symmetries in the transport matrix for toroidal plasmas, both with and without fluctuations. In the absence of fluctuations, new Pade´ approximates were found for the dependence of the bootstrap current and the ion thermal conductivity on the toroidal rotational velocity. With electrostatic fluctuations and the toroidal rotational velocities ordered to be on the scale of the ion thermal velocity, new symmetric transport matrices were derived with the additional thermodynamic force-flux pair of variables given by the shear in the toroidal angular velocity and the corresponding flux of toroidal angular momentum. The terms responsible for the turbulent transport of ion thermal energy and the toroidal plasma momentum were investigated in detail, and it was found that the effective Prandtl number for the system is 2/3 under general assumptions about ion-temperature-gradient turbulence. The Onsager symmetry of the transport matrix was found to hold whether or not the ambipolarity condition is used to reduce the number of conjugate pairs of fluxes and thermodynamic forces.

Test particle simulations for toroidal transport in reversed-shear plasmas—The transport properties of the fully nonlinear guiding-center equations for plasma transport, both with and without collisions and/or fluctuations, were investigated by means of test particle simulations in toroidal geometry with reversed magnetic shear. The fluctuations were modeled by the global toroidal eigenmodes as given from toroidal drift mode theory and observed in global particle simulations. The guiding center trajectories were obtained with high-order adaptive integrators. The transport was measured and characterized. It was found that the large orbits in the core produce a direct transport that is not characteristically diffusive. In the outer region where the orbits become the standard banana orbits, diffusion applies and the value of the diffusivity agrees with modern neoclassical formulas. This work has been applied to explain the reversed shear transport that was observed in TFTR experiments.

Discontinuity model for transport barrier formation in reversed shear tokamaks—Self-consistent electrostatic field calculations of the toroidal drift wave fluctuations driven by the ion temperature gradient have led to complex, radially extended convective cells defined as mesoscale structures in the saturated, nonlinear state. Qualitatively new features were found in reversed magnetic shear systems. On the left and right sides of the reversal layer, the quasi-coherent dynamical structures lead to a profile resiliency and a Bohm-like scaling for the turbulent transport in systems relaxed toward the critical gradient. A gap in the density of rational surfaces gives rise to disconnection of the structures on opposite sides of the q_{min} surface. The disconnection provides a radial zone of suppressed transport. When incorporated into the radial transport code, this feature allows the formation of the Type-2 internal transport barrier that produces the super-high fusion performance observed in the JT-60U tokamak. This work was performed in collaboration with the transport and simulation group at JAERI.

Confinement modes and bifurcation theory—A new high-resolution transport code written in Fortran 90 with MPI for the Cray T3E was designed and tested. The code combines simplified neoclassical and turbulent transport formulas to describe the fast bifurcations to various types of confinement regimes from the coupled partial differential equations. The control parameters are the externally injected power and its gradient, and the injected momentum and its gradient (which measures the injected vorticity from auxiliary heating sources). The relation between the transport equation for the plasma turbulence and the primitive ITG mode coupling equations was established through studies of the closure problem.

Transport in tokamaks with impurities—Transport studies of plasmas confinement with low-Z impurities (typically, carbon) were extended to include the parallel mass velocity shear. The role of the shear flow is to shift the eigenfunctions off rational surfaces, which in turn generates a Reynolds stress that creates poloidal shear flow. These effects are correlated with the improved confinement states found in plasmas with strongly sheared toroidal mass flow velocity in the DIII-D and JT-60U tokamaks.

Predictions of ITER performance from theoretical modeling with the ITER profile database—A new joint Cadarache-IFS project analyzed the newly released ITER Profile Database with ITG-based theoretical formulas for the ion thermal transport. The results showed the predicted performance of ITER for three models of ITG-trapped electron mode turbulence. The study used the ASTRA transport code, and comparisons were made with a similar study in collaboration with a group at Lehigh University group using the BALDUR code. Modeling theory showed that the level of validation of the models for the fixed data base is highest for the model with the fewest number of parameters. Both the level of error and the degree of validation were estimated in these studies.

Physics of low-aspect-ratio torsatrons and stellarators and torsatron/tokamak hybrids—Simplified models were developed from neoclassical theory and prompt orbit losses in order to estimate the electric field and resulting confinement for proposed operating scenarios of a device based on the so-called SMARTH concept, which relies on the radial electric field to control particle orbits and achieve confinement.

ITG simulations for DIII-D and C-MOD—The IFS/PPPL gyrofluid code was used to simulate ion-temperature-gradient turbulence for comparison with experiments on Alcator C-Mod and DIII-D. Initial applications to C-Mod were a more detailed look at a high-performance H mode and a comparison of cold pulse experiments with those done previously on the TEXT tokamak. On DIII-D, modulated ECH experiments were examined in an attempt to observe and predict modulation of the turbulence levels and their correlation with transport.

Macroscopic stability & plasma-boundary physics

The study of macroscopic MHD instabilities is especially important for designing the next generation of toroidal devices, since control of these modes extends hope for improving plasma performance. The IFS has made key contributions to recent advances in the understanding of resistive wall stabilization, error-field-driven magnetic reconnection, and tearing mode stability. The study of edge plasma physics is also important, with special relevance to L- to H-mode confinement transitions, improved confinement, divertor design for ITER, and other topics. IFS work in this latter area has been mainly done in association with the Joint Program in Divertor Physics.

Bifurcated states of a rotating tokamak plasma in the presence of a static error field—The bifurcated states of a rotating tokamak plasma in the presence of a static, resonant, error field are strongly analogous to the bifurcated states of a conventional induction motor. The two plasma states are the "unreconnected" state, in which the plasma rotates and error-field driven magnetic reconnection is suppressed, and the "fully reconnected" state, in which the plasma rotation at the rational surface is arrested and driven magnetic reconnection proceeds without hindrance. The response regime of a rotating tokamak plasma in the vicinity of the rational surface to a static, resonant, error-field was found to be determined by three parameters: the normalized plasma viscosity P, plasma rotation Q, and plasma resistivity R. Eleven response regimes can be distinguished, and their extents were calculated in *P-Q-R* space. In addition, an expression for the critical error field amplitude required to trigger a bifurcation from the "unreconnected" to the "fully reconnected" state was obtained in each regime. The appropriate response regime for low density, ohmically heated, tokamak plasmas was found to be the nonlinear constant-ψ regime for small tokamaks, and the linear constant-ψ regime for large tokamaks. The critical error field amplitude required to trigger error field-driven magnetic reconnection in such plasmas is a rapidly decreasing function of machine size, indicating that particular care may need to be taken to reduce resonant error fields in a reactor-sized tokamak. In NBI-heated plasmas it is possible to access more exotic plasma response regimes.

Effect of phase shifts on feedback stabilization for resistive shell mode—A formalism was developed for optimizing the design of feedback coils placed around a tokamak plasma in order to control the resistive shell instability. The type of feedback scheme has an array of rectangular saddle coils place immediately outside the shell. The effect of phase shifts between the feedback loops and the flux loops has been examined. In general the phase shifts have a beneficial effect, in some cases significantly reducing the critical feedback gain required for stabilization. This gives some measure of confidence that feedback stabilization schemes can be realized in practice.

Object-oriented MHD—The nonlinear MHD code "CTD" has been comprehensively rewritten with object-oriented methods for a massively parallel environment. The use of object-oriented techniques will allow switching among various physics models and geometries in an easy manner. The first applications of this new code were to resistive MHD, continuing earlier work on the vertical displacement events in shaped tokamaks.

Tearing mode stability for DIII-D plasmas—The tearing mode stability parameters for DIII-D discharges were calculated in the low- and high-mode-number regimes. Also, the nature of singularities in the Mercier stability criterion were elucidated. Access to the regime of second stability is controlled by the Mercier stability index. However, when this index becomes too negative (≤ 1), the conventional theory of tearing mode stability fails, this failure being manifested by a sequence of singularities in the magnetostatic matching data (delta-prime) that describe the free energy available to drive the mode. This singularity was resolved by extending the asymptotic analysis to higher order.

Particle canonical variables in terms of magnetic flux coordinates—Toroidal equilibria with nested flux surfaces are conveniently described in terms of magnetic flux coordinates. The poloidal and toroidal coordinates are not exact particle canonical variables unless the angles can be chosen so that the flux covariant component of the magnetic field is zero. Boozer has introduced a set of flux coordinates in which the poloidal and toroidal are good canonical variables, although approximate. Thus a canonical Hamiltonian description of particle guiding-center motion in toroidal geometry is often formulated in terms of Boozer coordinates. Here, this restriction was removed, and particle canonical variables were defined in terms of an arbitrary set of magnetic flux coordinates. The Hamiltonian equations of motion reproduce the guiding center drifts correctly to first order in a Larmor radius expansion. This formulation includes the presence of large perpendicular equilibrium electric fields.

Ballooning mode stability formulated in terms of VMEC coordinates—Stellarator equilibria in which particle trajectories are quasi-omnigenous have received much attention. These equilibria are most conveniently described in terms of "VMEC" flux coordinates. In this work, the ballooning stability of these equilibria was formulated in terms of VMEC flux coordinates rather than in terms of a set of straight-field-line flux coordinates, the goal being to construct an efficient scheme for determining the critical beta limits for ballooning stability.

Edge transport—In a continuing collaboration with scientists at MIT and Culham Laboratory, ion and impurity transport near the tokamak edge were examined, with allowance for neutral interactions (including charge exchange). The transport problem near the edge intrinsically involves a distinct ordering and cannot be treated by conventional transport equations.

Orbit distortion due to large electric fields, and its effect on transport—It is well known that electrostatic fields in tokamaks can vary on relatively short scale lengths, approaching the ion banana width. The resulting "squeezed" ion orbits are associated with significantly reduced neoclassical transport. It was found that an analogous process occurs, for steeper field variation, at the level of particle gyration: potentials varying on a scale comparable to the ion gyroradius distort gyro-orbits and thus modify classical transport. The gyro-distortion can take one of three forms, depending upon the sign and size of the electric field shear. Reduction in orbit width occurs only in a potential well. In this case, and with the assumption that the ion density and temperature vary slowly on the scale of the shrunken orbit, the classical ion heat flux was computed. The sharp variation of the potential required for this theory could result from steep electron temperature gradients near the separatrix of a spherical tokamak or a reversed field pinch.

Alpha particle physics

The physics of alpha particles, especially their collective interaction with Alfvén waves in toroidal plasmas, has been important in connection with the recent deuterium-tritium experiments on TFTR and JET, with beam and ICRF fast-ion experiments on JT-60U, DIII-D, and C-MOD, and also with the design effort for the ITER ignition device. IFS work in this area has been carried out by means of several collaborations with other institutions and also through the TTF Fast Particle Working Group and the ITER Alpha Particle Expert Group. Emphasis was placed on comparing experimental data with the predictions of analytic theory and nonlinear numerical simulations.

Nonlinear dynamical studies of the fishbone instability—A physics model of the fishbone instability has been developed that treats the wave-particle nonlinearity and the linear response of the resonant layer near the $q = 1$ surface self-consistently. The model employs a new analytic expression for the linear MHD response. This approach emphasizes the similarity between the linear evolution of the stable internal kink mode and the Landau damping of plasma waves. The model has been generalized to incorporate the nonlinearity of the resonant layer. This has made it possible to obtain the first self-consistent calculation of anomalous transport, as well of the characteristic frequency shift and mode amplitude, during a fishbone burst. Numerical simulations of both the diamagnetic as well as the precessional drift fishbone modes were carried out and found to correlated with experimental results: viz., significant losses in PDX, and strong redistribution without loss in JET. For ITER-like devices, strong alpha particle redistribution due to fishbones was predicted. The simulations also self-consistently reproduce the large nonlinear downshift in frequency ("chirp") that accompanies mode saturation.

Large-scale confinement simulation for ITER-like plasmas—Extensive numerical simulation in toroidal geometry was performed for the confinement of energetic alpha particles that experience both anomalous TAE- and fishbone-driven transport in reactor-class ITER-like plasmas. The high-mode-number, core-localized TAE modes are expected to be potentially dangerous in ITER. However, so far the simulation results have shown that even in scenarios where the linear growth rates were taken to be ten times higher than the expected values, no alphas were lost and radial redistribution was negligible.

Numerical simulation of spontaneous formation of universal phase-space structures—The formation of phase-space holes and clumps, caused by energetic particle-driven instabilities, has been simulated. The full simulation package has been made available via public FTP, and it runs on any UNIX platform equipped with Tcl/Tk, C++, and IDL. The code has been installed at the JET Joint Undertaking for use in understanding the nonlinear behavior of ICRH and beam-driven TAE modes.

Hole-clump dynamics with collisions—Previously it was shown that kinetic instabilities can produce nonlinear phase space structures (holes and clumps) that give rise to large frequency shifts of the unstable mode. A collisionless adiabatic theory showed that such a structure is a constant-amplitude BGK mode, with background dissipation balanced by the power extracted from the kinetic component by a moving phase-space "bucket." The theory has been extended to describe the collisional processes that eventually destroy the phase-space structures.

Interpretation of pitchfork splitting effect—A theoretical explanation was found for the TAE pitchfork splitting phenomenon that was observed in JET deuterium-tritium experiments. In these experiments, the unstable TAE mode first reaches a saturated nonlinear level and then its single spectral line splits into several closely-spaced spectral components. The IFS theory describes the dynamics of the transition and relates the amount of splitting and the amplitudes of the sidebands to the linear instability growth rate and the effective collision frequency of the resonant ions. The values of the growth rate and the collision frequency inferred from this comparison were consistent with independent experimental measurements and estimates. This suggests the interesting possibility of using the pitchfork effect as a diagnostic tool.

Distributed parallel algorithm for fast-particle weak turbulence studies—Software that enables the parallelization of specific previously-existing particles codes, viz., for the bump-on-tail, TAE, and fishbone instabilities, was developed. The computational workload is distributed in parallel to a pool of N client workstations. Each client performs a fraction of the computation, using an identical C++ code, with the overall simulation managed by a central Java-based server (for multithreading). For sufficiently large particle number, the performance was found to scale linearly with the number of available floating point operations per second. The efficiency of the distributed time-stepping algorithm relies on the rather special nature of the energetic particle nonlinearity. Detailed simulation results have been obtained with this algorithm for the spontaneous formation of phase-space holes and clumps in a weakly unstable 2-D plasma.

Basic plasma physics & interdisciplinary research

Basic plasma physics is a broad category that includes fundamental discoveries, as well as numerical methods for modeling aspect of plasma behavior. In addition, due to the interdisciplinary nature of plasma physics, the IFS has been involved in research in a number of neighboring fields, such as nonlinear fluid dynamics, astrophysics and cosmology, low-temperature plasma science, laser plasma accelerators, solid-state and cluster plasmas, and computational science. Thus, IFS work provides a bridge between fusion science research and the wider scientific community.

Diamagnetic structures in two-fluid MHD—The well-known case of stationary (no-flow) force-free magnetic field satisfying the Beltrami condition was extended to a new regime of double-curl Beltrami flow. Due to strong coupling between the fluid-kinetic and magnetic aspects of the plasma, it was discovered that highly confining, fully diamagnetic, and everywhere minimum-B configurations can emerge, with scale lengths of a few ion

Debye lengths. These extremely compact diamagnetic structures should to be MHD-stable, being states of lowest free energy. Alternative pressure-confining magnetic field configurations such as these may point to a new path in the quest for thermonuclear fusion. The parameters characterizing these novel equilibria can be related to physical constraints of the system, such as the total plasma current and toroidal momentum, in order to obtain 1-D and 2-D equilibria as a function of realistic control parameters.

Light bullets in electron positron-ion plasmas—Electromagnetic wave dynamics in a relativistic electron-positron plasma are essential to determine the radiation characteristics of astrophysical objects ranging from pulsars to galactic nuclei. A minority population of heavy ions can also be present and impart interesting features, such as the existence of large-amplitude spatially and temporally localized structures, called "light bullets." These structures were found to be robust in the sense that they are stable and can be generated from a variety of initial conditions. It was also shown that when two of them collide, either they survive intact or they pass through each other in a quasi-solitonic fashion, "fusing" into a third bullet. Trains of these bullets impart considerable inhomogeneity to the medium in which they are born and propagate, which may possibly account for the "clumpiness" observed in jets emanating from black holes.

Hamiltonian methods applied to contour dynamics—Various fluid and plasma models can be described by "contour dynamics" (waterbag). The application of Hamiltonian methods was found to reduce the infinite system to ordinary differential equations that are Hamiltonian, which greatly facilitates calculations. This technique has also been applied to generalizations of the Kirchoff ellipse, multi-contour vortices (with or without the beta effect), and other cases of atmospheric and oceanographic relevance. Another technique—viz., moment truncations of fluid equations—has also been explored for obtaining finite Hamiltonian systems from partial differential equations. This method was applied to models that describe long-lived vortices relevant to ocean transport—in particular, vortices known as "Meddys," which originate in the Mediterranean Sea and last for up to several years.

Singular eigenfunction techniques for fluid and plasma problems—The linear stability of inviscid, incompressible, two-dimensional, plane-parallel shear flow was considered over a century ago by Rayleigh, Kelvin, and others, who derived necessary conditions for instability. In recent work a solution was finally achieved for the classic problem of deriving a condition that is both necessary and sufficient for the Rayleigh equation.

Strong echo effect in shear fluid flows—In two-dimensional Couette flow, two disturbances excited successively can interact nonlinearly to produce a transient energy growth that occurs long after the energy associated with the original disturbances has decayed. This "echo effect," which is a nonlinear ramification of the continuous spectrum, was studied for the case when the nonlinear response has the same order of magnitude as the two original excitations. Viscous dissipation can influence the echo effect.

Nonlinear stability of ion acoustic waves—Lyapunov stability of the full fluid system (not just the usual Korteweg-deVries limit) was investigated. The equilibrium is shown to be a critical point of a free energy functional, although negative energy modes persist at short wavelengths. Explicit solitary and periodic wave solutions to the ion-acoustic equations with pressure are found for the first time. Solitary wave solutions can exist at Mach numbers much higher than for the case without pressure.

Cluster plasmas—Irradiation of clustered material by modern ultrashort laser pulses causes the material to become ionized ("cluster plasmas") and emit very intense, multiple-harmonic X-rays. It was found that, unlike an ordinary gas plasma or an electron plasma in a metal, a cluster plasma allows propagation of electromagnetic waves below the plasma cut-off. The properties of these waves may be useful as a novel particle acceleration method that does not use an induced longitudinal field and also as a phase-matching method for waves of different harmonics.

Testing Unruh radiation with ultra-intense lasers—In ponderomotive acceleration, electrons are accelerated from a cold start to near the speed of light in a fraction of a picosecond. This violent acceleration, on the order of 10^{21} g, is that same as that found near the horizon of a black hole. It was pointed out that such accelerations, soon to be obtainable with intense ultrafast lasers, could produce Unruh (vacuum fluctuation) radiation, which could then be detected by taking advantage of its specific dependence on the laser power and characteristic spectral-angular distribution. This would permit the exciting possibility of testing general relativity and the structure of the vacuum in a laboratory setting.

Substorm trigger conditions—The onset of magnetospheric substorms in the stressed geomagnetic tail is attributable to plasma instabilities. The MHD stability of a 2-D equilibrium model of the geomagnetic tail with large plasma beta was investigated. Preliminary calculations indicate that the high-beta region is stable due to compressibility and that substorms triggered by MHD instability may occur at the near-Earth edge of the central plasma sheet of the magneto-tail where the plasma beta is of order unity.

Field-Reversed Configuration and space plasma physics transport—Transport studies of the plasmas confined by the naturally occurring reversed magnetic field configuration formed by the solar wind interaction with the Earth's magnetic field were performed. Comparisons were made with results from laboratory FRC experiments at Los Alamos National Laboratory. Detailed particle and field measurements have been provided by satellites that traversed the core of the very high-beta reversed magnetic field configuration. Transport analysis of the system indicates an ion orbital viscosity effect that gives the collisionless transformation of the crossfield mass flow kinetic energy into thermal ion energy through the sheared flows. Comparisons were carried out with a standard space plasma physics database.

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