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ESTABLISHMENT OF AN INSTITUTE FOR FUSION STUDIES

Technical Progress Report

November 1, 1991 - October 31, 1992

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"Establishment of an Institute for Fusion Studies"
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Introduction

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 center for information exchange, nationally and internationally, 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 that are obtained by the Institute contribute mainly to the progress of national and international efforts in nuclear fusion research, whose goal is the development of fusion power as a basic energy source. In addition to its primary focus on fusion physics, the Institute is also involved with research in related fields, such as advanced computing techniques, nonlinear dynamics, plasma astrophysics, and accelerator physics. The work of IFS scientists continued to receive national and international recognition. Numerous invited papers were given during the past year at workshops, conferences, and scientific meetings. Last year IFS scientists published 95 scientific articles in technical journals and monographs.

The Institute actively sponsors collaborative research programs with laboratories and universities throughout the U.S. and the world. Last year, the IFS hosted 41 short-term visitors and 27 long-term (i.e., one month or more) visitors. In particular, on behalf of the Department of Energy, the IFS is the principal site in the United States for the exchange activities of the U.S.-Japan Joint Institute for Fusion Theory. Each year this program normally includes two workshops in each country, six exchange scientist visits, and several joint computational projects on the US-Japanese international computer data link.

In addition to its research activities, the IFS has a significant educational function. Last year 17 graduate students worked on fusion and plasma physics thesis-degree projects under the supervision of senior IFS scientists, who also teach courses in the Physics Department. Three of these students graduated with Ph.D. degrees last year. Also, as part of its educational role, the Institute has a postdoctoral training program, which involved 9 postdoctoral fellows last year.

Technical Progress and Results

During FY 1992, a number of noteworthy scientific advances were achieved, relative to both long-range fundamental problems as well as near-term issues. Examples of these achievements include studies of ion temperature gradient driven turbulent transport, alpha-particle driven toroidal Alfvén eigenmode stability, simulations for the Numerical Tokamak Project, and mathematical physics. Many of these projects were done in collaboration with scientists from other institutions. Important research discoveries (concerning which space limitations allow only brief and selective description) were attained in the following areas:

1. Tokamak Dynamics

The nonlinear evolution of the $m = 1$ mode was examined in high-temperature plasmas where the mode is either in the semi-collisional or collisionless regime. In either regime, the mode exhibits nonlinearly enhanced growth rates that far exceed their linear values, thus making their nonlinear evolution collisionless. This accelerated growth may explain the fast sawtooth crashes observed in large tokamaks.

Investigation was continued of a novel method proposed for stabilizing or reducing the growth rate of $m = 1$ tearing modes by means of resonance detuning caused by jittering the rational surface. A kinetic treatment of this method revealed several new features, including the need for external forcing of electrons to prevent runaway.

A kinetic theory of rf current drive and helicity injection showed that a wave helicity flux perpendicular to the magnetic field does not influence the parallel motion of electrons to leading order and therefore will not drive a significant current. This result is relevant to the quest for efficient current drive methods in a tokamak.

The behavior of tearing instabilities in the presence of equilibrium flow and X-point reconnection was analyzed in slab geometry. A nonlinear MHD code exhibits the existence of oscillating islands. With current-free X-points, there is either relaxation back to equilibrium or instability to the formation of current sheets.

Reduced fluid models, based on the large aspect ratio approximation, were studied with the use of Hamiltonian perturbation theory and action principles.

The field lines of tokamak poloidal divertors were studied with the use of integrable area-preserving maps. These results are useful for understanding the effect of electromagnetic limiter fields on the divertor, e.g., in the TEXT tokamak.

2. Edge physics

The effects of charge-exchange processes, which are believed to play a key role in determining appropriate boundary conditions on plasma transport, were calculated. In particular, an analytical kinetic theory of neutral density profiles at long charge-exchange mean free path, as well as a generalized theory of ion rotation damping, are being developed.

Also, the question was examined of how the ion density varies near the separatrix in a divertor tokamak, where large values of the safety factor imply that all ions are into the collisional regime, regardless of pitch angle.

Kinetic theory was developed for the edge region in tokamaks where the electrostatic potential varies radially on the scale length of the poloidal gyroradius; this theory allows the effects of orbit squeezing and enhanced trapping on ion transport to be taken into account. Monte-Carlo simulations of ion orbits in the edge electric field are underway.

Also, the description of a toroidally rotating tokamak plasma was generalized to allow for rapid poloidal rotation, which is apparently associated with edge effects.

The conducting end-wall electron temperature gradient instability was applied to the scrape-off layer of a tokamak, yielding results consistent with the scrape-off width observed in experiments.

Edge turbulence was studied from the point of view of mode identification and driving source. It was shown that the dissipative drift wave can be destabilized by impurity condensation associated with radiative cooling. Also, the potential drive due to ionization is strongly dependent on the manner in which the equilibrium is achieved. Both of these conclusions contradict earlier results that had been proposed elsewhere. In related work, turbulence suppression by arbitrary shear flow was found to occur essentially at moderate values for the shear flow.

3. Turbulence and Plasma Transport

Analytic studies of ion temperature gradient driven transport were continued. The effect of anisotropy in the ion temperature and that of temperature gradient were examined for the toroidal η_i mode. A fully kinetic and nonlocal description of this mode was obtained from a numerical solution of the gyrokinetic equation in ballooning space. In the electromagnetic regime, a new mixing length formula was proposed to explain the experimentally observed radially increasing profile and the parameter scaling for the ion thermal conductivity $\chi_i(r)$. Electromagnetic effects on the toroidal electron temperature gradient driven modes were studied and found to be destabilizing, unlike in slab geometry. Also, the kinetic η_i mode was studied in the presence of ion flow shear: poloidal flow shear was found to be stabilizing, whereas toroidal flow shear is destabilizing, which is in qualitative agreement with experimental observations on edge turbulence. The effects of impurities were also examined.

A large project on analyzing drift wave and η_i mode stability and transport in the TFTR tokamak density modification experiments was completed in collaboration with Princeton experimentalists. This analysis showed that the η_i mode can explain the experimental power balance in transport in these high- T_i , high- $-\nabla T_i$ experiments, earlier thought to disagree with theory.

The ion temperature gradient mode was investigated numerically with the use of the TPC particle code, for the case of a flat density profile, in order to simulate the behavior of an H-mode tokamak plasma.

The neoclassical viscosity effect on conventional resistive tearing and resistive ballooning modes was studied by the derivation and numerical solution of the linearized flux-surface-averaged resistive MHD boundary layer equations, including the neoclassical viscosity, the diamagnetic drift, and the compressibility terms in general toroidal geometry.

A major new direction in the solutions for drift wave vortices in a shear magnetic field was discovered. Both theory and simulations show the validity of the concept of drift wave vortices in such a sheared field.

A new model was developed for the nonlinear interactions of multiple-helicity versus single-helicity drift waves. The theory indicates that single-helicity modes play a dominant role in establishing the radial profile of the anomalous transport. This model introduces the density of states for the localized drift waves and shows that it leads to strongly radially increasing profiles for the thermal diffusivities.

The transport caused by the emission and absorption of electron plasma waves was studied by considering the wakefield of a superthermal test electron in a magnetized plasma. An enhancement of the transport of momentum and energy due to such waves was found that exceeded the level that had been previously predicted elsewhere.

Tokamak transport in a turbulent electromagnetic field was analyzed with neoclassical effects taken into account. The transport coefficients so obtained are weakly sensitive to the spectrum and amplitude of the fluctuations and may explain anomalous ion transport in a tokamak.

Particle trajectories in a toroidal system with strong poloidal and toroidal asymmetry was investigated. This study is the basis for analyzing transport in a tokamak under ECRH heating or with vertically asymmetric field ripple (which can occur for a vertically displaced plasma column).

4. Computational Plasma Physics

The IFS became a partner in a multi-institutional consortium for a joint project to develop a "numerical tokamak," which would simulate turbulent transport in the core plasma. This grand-challenge project is part of a program of research related to the current High Performance Computing and Communications Initiative of the federal government.

In particular, the IFS continued to be active in the development of a large-scale numerical tokamak model with the TPC code, a toroidal-geometry, general-coordinate-metric, particle-simulation code. TPC simulations of heat transport and particle diffusion induced by η_i modes were found to give perhaps the first-ever numerical results for the ion thermal diffusivity that have the same value and radial profile as in experimental observations. Correlations with observed fluctuation spectra indicate that toroidal mode coupling may explain the observed heat transport. The TPC code is being augmented with gyrokinetic and low-noise ("delta-f") algorithms, as well

as a Darwin-type model for representing self-consistent magnetic fields. Also, a portable scientific plot package used by the TPC code is being released in beta test form to users at other institutions. In a collaboration with the Microelectronics and Computer Technology Corporation, the TPC code is being used to test new MCC software for distributed computing.

A parallel effort to develop a particle simulation code for studies of transport and stability in full toroidal geometry was initiated. So far, an electrostatic version with a full-dynamics pusher for electrons and ions that uses conventional algorithms, a full-dynamics pusher with a low-noise ("delta-f") algorithm, and a model with drift-kinetic electrons that uses either a conventional or a delta-f algorithm has been constructed and tested. The progress of this effort (as well as the TPC program) has been greatly facilitated by the extensive utilization of high-performance work stations that the Institute purchased last year.

A three-dimensional gyrokinetic spectral code was also employed to simulate the turbulence driven by the ion temperature gradient instability in a toroidal annulus. It was found that thermal diffusivities in toroidal geometry are much larger than previous results in slab geometry and are approaching experimentally observed values.

5. Alpha Particle Physics

A topic of great concern to proposed ignition experiments like ITER, as well as to D-T operation in the TFTR and JET tokamaks, is the behavior of the toroidal Alfvén eigenmode. Previous work at the IFS had predicted that these waves can be strongly excited by alpha particles, which was confirmed by recent experiments at Princeton and General Atomics that used neutral beam-injected fast ions to simulate the alpha particles. Current IFS studies have studied several aspects of the TAE modes. A high-mode-number theory was developed to calculate self-consistently their damping due to resonance with the shear Alfvén continuum. The inclusion of electron parallel dynamics was shown to be able to influence the TAE damping rate, through coupling to the kinetic Alfvén wave under conditions that depend on the gap size, the shear, the magnitude of the parallel conductivity, and the mode numbers. The finite size of the alpha particle orbit excursion from a flux surface, which can cause a decrease in the interaction strength when the orbit size is comparable to or larger than the mode width, was taken into account in estimating the destabilization of TAE's in an ignition plasma. Mapping methods were developed to describe the nonlinear dynamics of the interaction of alpha particles and Alfvén waves. Stochasticity thresholds were estimated, and the quasilinear problem was addressed. In particular, scenarios for alpha particle evolution were defined, ranging from benign pulsations, to phase-space explosions in which the alpha particles rapidly diffuse radially to the outer region of the plasma. Also, in collaboration with General Atomics, an Alfvén wave numerical code is being extended to toroidal geometry, with the goal of studying antenna-driven TAE and GAE modes, as well as their utility for current drive.

The strong electric field that is usually observed near the edge of an H-mode tokamak plasma was found to modify the dispersion curves of the toroidal shear Alfvén wave significantly: when the radial electric field shear in the $E \times B$ drift overcomes magnetic shear, the Alfvén “gap” mode disappears, and two resonances arise that lead to a Kelvin-Helmholtz instability.

A new mechanism, viz., the two-energy-stream cyclotron instability, by which fast ions (e.g., fusion-product protons or alpha particles) can excite electrostatic Bernstein waves was investigated. This mechanism yields a possible explanation for the ion cyclotron emission observed in experiments on the JET tokamak with D-D and D-T fueling.

6. Nonlinear Dynamics and Mathematical Physics

The free energy principle for nonlinear instability of neutral negative-energy modes was obtained, and an expression for the free energy in terms of the electric field and for the case of incompressible fluids was derived. Arnold diffusion was investigated as a mechanism for nonlinear instability to arbitrarily small perturbations, which is completely overlooked by conventional linear stability analysis when negative energy modes are present. Contour dynamics, a model that contains much of the physics of vortex dynamics, was employed to find the existence of negative energy modes.

The symplectic structure of the Vlasov equation was investigated. With the use of the Hamiltonian structure, a phase space description that is similar to that for quantum mechanics was obtained for the first time for Maxwell's equations.

Explicit solutions, both analytical and numerical, were found for the nonlinear Vlasov-Poisson system that describe the time evolution of an inhomogeneous collisionless plasma. The solution is given in terms of a double perturbation series, with the infinite sum of interaction terms performable exactly due to the property of dynamical factorization.

7. Advanced Ideas

The stability of “compact” (i.e., with finite axial length) field-reversed configurations for confining a plasma whose ions consist mostly of an energetic beam component was analyzed; the potential for ignition in this novel concept of a self-collider is being studied. Another interesting advanced concept that had been proposed for plasma confinement, a “magnetless” system, was further explored.

A theory for describing high-Reynolds-number MHD fluids in terms of magnetic filaments was developed.

The limits of validity for the well-known ballooning representation were systematically analyzed for toroidal drift waves in a non-ideal plasma.

A theoretical description was given for the amplification mechanism of the ion-ripple laser, which is an advanced scheme for generating coherent high-power radiation.

A new idea for using a mirror machine as a neutron source was proposed. To obtain high Q in a mirror neutron source, the electron temperature needs to be about or greater than 2 keV. Typically, however, open-ended mirrors have an electron temperature that is an order of magnitude less than this. In this new proposal, an elliptically elongated toroidal link contains the electrons in a low beta region, while minimum-B fields are used in the high-beta region. In this way, it may be possible to achieve large neutron flux with high efficiency.

Some work was done on plasma theory applied to high-energy particle accelerators. A theory for noise in the rf system of the SSC collider rings was applied to the growth of longitudinal emittance due to intrinsic sources of noise and its contribution to luminosity loss, and to the extraction of low-intensity beams from the SSC for fixed target physics. A proposal for an experimental test of these ideas on the Tevatron was recently approved.

Fluid mechanical analogies of nonlinear drift wave dynamics were explored. A "standard non-twist" map was derived that exhibits separation reconnection and an unusual path to global chaos. This map is relevant to finite-degree-of-freedom Hamiltonian system techniques, which describe transport of dye in rotating tank experiments.

Conclusion

Institute work continued to receive national and international recognition. At the 1991 APS Plasma Physics Meeting, T. Tajima presented an invited paper, "On Zero Frequency Magnetic Fluctuations in Plasmas" and A. Beklemishev presented an invited paper, "Anomalous Ion Thermal Diffusion from η_i Modes". At the 1992 Annual Controlled Fusion Theory Sherwood Conference, invited papers on "Map Model for Nonlinear Alpha Particle Interaction with Toroidal Alfvén Eigenmodes", by H. Ye and "Nonlinear Drift Wave Structures in a Sheared Magnetic Field", by X. Su were presented. Numerous invited papers given during the past year at other workshops, conferences, and international meetings could also be cited.

Although the Institute for Fusion Studies has no formal programmatic or experimental support responsibility, it does contribute to the national and international fusion scientific effort in a variety of ways. Close collaborative relationships have been developed with university and national laboratory fusion groups, both in the US and abroad. Advanced theoretical and computational techniques are being developed and disseminated; a broad spectrum of confinement devices are being investigated; and, in addition to primarily fusion plasma physics work, contacts are being maintained with the fields of fluid dynamics, computational mathematics, statistical mechanics, accelerator physics, and space physics. The diversity of the research performed at the Institute is reflected in the attached list of recent IFS publications.

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BIALYNICKI-BIRULA, Iwo	Polish Academy of Sciences	Sept. 11-21, 1991
BREIZMAN, Boris	Inst Nucl Phys., Novosibirsk, RUSSIA	January 8, 1992-January 1, 1993
CARY, John	Univ. of Colorado, Boulder	Feb. 6-7, 1992
CHEUNG, L.	Tunghei Univ., Taiwan	Sept. 1, 1991-August 31, 1992
CHOI, Duk-In	KAIST, Korea	July 17-19, 1991
COWLEY, Steve	Princeton Plasma Phys. Lab	October 13-15, 1991
COWLEY, Steve	Princeton Plasma Physics Lab	February 25-28, 1992
CRAWFORD, John D.	University of Pittsburgh	January 5-10, 1992
CRAWFORD, John David	University of Pittsburgh	April 30-May 16, 1992
DENTON, Richard	Dartmouth College	March 25-27, 1992
DEWAR, Robert	Australian National University	Nov. 9, 1991-Jan. 24, 1992
DIMITS, Andris	Lawrence Livermore Natl Lab	March 4-6, 1992
DRAKE, Jim	University of Maryland	February 24, 1992
ERNST, Darin	MIT	June 24-August 31, 1991
EROKHIN, N.S.	Space Research Institute, Moscow	July 15-24, 1991
ESIPCHUK, Yu. V.	Kurchatov Institute, Moscow	Sept. 22-Nov. 3, 1991
HAMANATSU, Kiyotaka	J.A.E.R.I., Japan	March 11-13, 1992

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<u>Name</u>	<u>Institution</u>	<u>Dates of Visit</u>
HOJO, H.	Univ. of Tsukuba, Japan	March 19-April 26, 1992
HUA, Daniel	Univ. of California, Berkeley	October 12-14, 1991
ICHIGUCHI, Katsuji	Natl. Institute for Fusion Science, Nagoya, Japan	April 1-4, 1992
ICHIKAWA, Yoshi	Natl. Inst. for Fusion Science, Nagoya, Japan	August 11-17, 1991
IYOSHI, Atsuo	Natl. Inst. for Fusion Science, Nagoya, Japan	October 29-30, 1991
ISHIGURO, S.	Tokoku Univ., Sendai Japan	Sept. 19-Oct. 3, 1991
ITO, Masataka	Tokyo Gakugei Univ., Japan	Aug. 15, 1991-Jan. 9, 1992
JACKSON, G.L.	General Atomics, San Diego	December 9, 1991
JOVANOVIĆ, Dusan	Inst of Physics, Czechoslovakia	April 8-June 10, 1992
KIESLING, Michael	Dartmouth College	March 2-3, 1992
KIM, Yil Bong	UCSD, Dept of Physics	November 25, 1991
KISHIMOTO, Yasuaki	J.A.E.R.I.-Japan	Nov. 10,'91-Nov.8,'92
KOTELNIKOV, Igor	Inst. of Nucl. Phys., Novosibirsk, Russia	Sept. 29-Dec. 25, 1991
LIU, Jixing	Academia Sinica, Beijing, China	May 1-August 1, 1992
MASCHKE, Eric	Cadarache, France	April 11-30, 1992
MATSUMOTO, Ryoji	Chiba University, Japan	Aug. 5-Sept. 27, 1991
MATSUMOTO, Ryoji	Chiba University, Japan	March 11-April 8, 1992

IFS VISITORS -1991-92

<u>Name</u>	<u>Institution</u>	<u>Dates of Visit</u>
MEERSON, Baruch	Hebrew Univ. of Jerusalem, Israel	January 7-February 12, 1992
MINESHIGE, S.	Univ. of Tokyo, Japan	July 19-29, 1991
MOISEEV, S.	Space Research Institute, Moscow	July 15-24, 1991
NAKAMURA, Yuji	Kyoto University, Japan	Nov. 9-December 4, 1991
OHNISHI, Masami	Kyoto University, Japan	July 25-Sept. 1, 1991
PASTUKHOV, Vladimir	Kurchatov Institute, Moscow, Russia	Jan. 24-April 22, 1992
PETVIASHVILI, Nickolay	Schmidt Inst. of Phys of the Earth, Moscow	June 28-Aug. 31, 1991
PETVIASHVILI, Vladimir	Kurchatov Inst., Moscow, Russia	August 11-17, 1991
PFIRSCH, Dieter	Max-Planck IPP, Germany	March 1-31, 1992
PORCELLI, Franco	JET, Culham, England	March 8-April 5, 1992
ROSTOKER, Norman	Univ. of California, Irvine	April 1-June 30, 1992
SCOTT, Steven	Princeton Plasma Physics Lab	February 10, 1992
SEDLACEK, Zdenek	IPP Czechoslovak Academy of Sciences	March 15-June 15, 1992
SHAING, Ker-Chung	Oak Ridge National Lab	October 19-25, 1991
SHAING, Ker-Chung	Oak Ridge National Lab	March 29-30, 1992
SMITH, Ralph	UCSD, La Jolla	March 10-12, 1992
TAKAMARU, H.	N.I.F.S., Nagoya, Japan	April 1-4, 1992

IFS VISITORS -1991-92

<u>Name</u>	<u>Institution</u>	<u>Dates of Visit</u>
TANAKA, Motohiko	N.I.F.S., Nagoya, Japan	January 13-24, 1992
TANI, Keiji	J.A.E.R.I., Japan	March 11-13, 1992
TANIUITI, TOSIYA	Nagoya, Japan	Feb. 9-April 1, 1992
TASSO, Henri	Max-Planck Institut fur Plasmaphysik, Germany	January 12-31, 1992
TAYLOR, Bryan	United Kingdom	Nov. 8-14, 1991
TAYLOR, Bryan	United Kingdom	April 9-23, 1992
THYAGARAJA, A.	Culham Laboratory, United Kingdom	March 16-18, 1992
TSIDULKO, Yuri	INP, Novosibirsk, Russia	May 6-July 20, 1992
WAELEBROECK, F.L.	Univ. of Maryland	Sept. 17-Oct. 2, 1991
WARE, Andrew	Univ. of California, San Diego	April 23-24, 1992
WONG, King Lap	Princeton Plasma Phys. Lab.	October 19-21, 1991
XU, Xue	Univ. of California, Berkeley	April 2-3, 1992
YUSHMANOV, P.N.	Kurchatov Institute, Moscow, Russia	Sept. 22-Nov. 3, 1991
YUSHMANOV, P.N.	Kurchatov Institute, Moscow, Russia	January 12, 1992 (for 2 years)
ZAKHAROV, Leonid	Kurchatov Institute, Moscow, Russia	April 9-10, 1992
ZONCA, Fulvio	ENEA, Frascati	April 9-10, 1992

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