ORNL/TM-12209

OAK RIDGE
NATIONAL
LABORATORY

MARTIN MARIETTA

TRANSPORT MECHANISMS ACTING IN TOROIDAL DEVICES: A THEORETICIAN'S VIEW

B. A. Carreras

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/TM-12209
Dist. Category UC-427

206

Fusion Energy Division

TRANSPORT MECHANISMS ACTING IN TOROIDAL DEVICES: A THEORETICIAN'S VIEW

B. A. Carreras

DATE PUBLISHED: January 1993

Prepared for
Office of Fusion Energy
Budget Activity No. AT 05

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

CONTENTS

PREFACE

This report is an extended version of a paper presented at the 19th European Physical Society Conference on Controlled Fusion and Plasma Physics, Innsbruck, Austria, June 29–July 3, 1992. A shorter version appears in the conference proceedings.

ABSTRACT

Understanding the basic mechanisms of transport in toroidal confinement devices remains one of the more challenging scientific issues in magnetic confinement. At the same time, it is a critical issue for the magnetic fusion program. Recent progress in understanding fluctuations and transport has been fostered by the development and use of new diagnostics, bringing new perspectives on these studies. This has stimulated new theoretical developments. A view of the most recent issues and progress in this area is given. The role of long wavelengths in core transport and the relation between shear flows and turbulence at the plasma edge are the primary topics considered.

1. INTRODUCTION

Anomalous transport in magnetically confined plasmas is probably caused by plasma turbulence. Experimental proof of this requires detailed measurements of plasma fluctuations and fluxes. In recent years, considerable progress has been made in the study of fluctuations and anomalous transport and in trying to bring theory and experiment closer. In comparing analytical models with experiments, one encounters some generic difficulties. The first one is that there are very few complete theoretical analyses of turbulent processes in plasmas. Most theoretical works have been focused on linear properties of instabilities, and the inferences for transport are based on the $\gamma/k_\perp^2$ ansatz. Another problem is the limited range of validity of theoretical models. The analytical calculations are carried out for well-defined regimes, while experiments run over multiple regimes. Therefore, one must beware of quick acceptance or rejection of theoretical models based on a single experimental test. Furthermore, the level of agreement with experiment shown by many transport models is directly proportional to the amount of empirical input included in these models. Agreement with experiment is an essential and real test for the models derived from first principles, but for empirical models, it is only a consistency test. The joint work of theoreticians, experimentalists, and modelers is needed in facing these problems. In some recent reviews of the subject of fluctuations and transport (CALLEN, 1990, 1992; WAGNER, 1992) and of some particular aspects of it (HAWRYLUK, 1991; WOOTTON, 1992a), the reader can find detailed accounts of the progress being made. Here, I try to give a perspective on the most recent issues and progress in this area.

In Sect. 2, some recent experimental results on core fluctuations and confinement are discussed. The role of long wavelengths has emerged as a critical question in understanding transport. Theoretical models are presented in Sect. 3. The plasma edge transport is briefly discussed in Sect. 4. In this area, one of the more active topics of research is the effect of flows on turbulence and the potential relation of this effect to the transition from low (L-mode) to high (H-mode) confinement (L-H transition). This topic is discussed in Sect. 5. In Sect. 6, a comparison of tokamak and stellarator transport is presented. Finally, the conclusions are given in Sect. 7.

2. PLASMA CORE FLUCTUATIONS AND TRANSPORT: PHENOMENOLOGY

One of the facts emerging from the plasma core fluctuation and transport studies is that long-wavelength fluctuations with long radial correlation lengths are present and play a role in controlling the core plasma transport. The present evidence comes from several experiments: (1) empirical scaling studies using dimensionally similar discharges, (2) electron temperature measurements, and (3) direct measurement of the radial correlation lengths of the core plasma fluctuations.

In exploring the fundamental transport mechanisms in tokamaks, an important experimental approach is the use of dimensionally similar discharges (WALTZ, 1990;

PERKINS, 1990). The objective is to identify the scaling of the transport coefficients on the dimensionless plasma parameters ρ_s/a, β, ν^*, ..., by producing discharges with all dimensionless parameters the same, except for one that can be varied from discharge to discharge. The goal of the initial experiments has been to isolate the dependence of the diffusion coefficient on the radial scale length of the turbulence. If the characteristic length of the turbulence depends only on plasma parameters, it will scale as the gyroradius ρ_s, and the corresponding diffusivities will have a gyro-Bohm scaling, $\chi = \left(\rho_s^2 V_{th}/L\right)F(\beta, \nu^*, ...)$. However, if the characteristic length of the turbulence scales with the size of the device, the corresponding diffusivity will have a Bohm-like scaling, $\chi = \left(\rho_s^2 V_{th}\right)F(\beta, \nu^*, ...)$. Detailed transport scaling experiments have been carried out in the Tokamak Fusion Test Reactor (TFTR) (PERKINS, 1992), the DIII-D tokamak (WALTZ, 1992), and the Joint European Torus (JET) (CORDEY, 1992). Results from TFTR are plotted in Fig. 1. Bohm scaling is the simplest interpretation of these experiments. However, it is necessary to remark that the variations in ρ_s are small, and similarity conditions and profiles are good but are not yet perfect. The present experimental evidence points to tokamak transport lengths that scale with the plasma minor radius.

The experimental resolution in the measurement of electron temperature profiles is increasing, and it is possible to resolve length scales on the order of 1 cm. These measurements have brought forward more evidence of the presence of structures with long radial lengths in the plasma core. The measured electron temperature profiles in JET (NAVE, 1992) and TFTR (GREK, 1991) in high-q operation indicate the existence of numerous flat spots, a few centimeters in size, in the profile.

In TFTR, microwave scattering experiments (BRETZ, 1988) have shown that the fluctuation spectrum is dominated by the long wavelengths (HAWRYLUK, 1991). However, the range of $k_\perp$ that can be spatially resolved by this diagnostic is limited. To explore the long-wavelength range ($k_\perp < 2$ cm^{-1}), density fluctuation measurements are being made using beam emission spectroscopy (BES) (FONCK, 1990; PAUL, 1990). These measurements show fluctuation levels in the range 0.1% to 1.0% in the plasma core in standard L-mode discharges, in agreement with other diagnostic measurements. Over the whole plasma radius, the measured radial and poloidal correlation lengths of the turbulence are about 2 cm, many times ρ_i (Fig. 2). The turbulence is anisotropic, with the poloidal k spectrum peaking at $k_\theta \cong 2$ cm^{-1} and the radial k spectrum at $k_r \cong 0$ (FONCK, 1992). The propagation in the poloidal direction is slow, and the decorrelation times are on the order of 10 ms to 100 ms. These measured plasma core density fluctuation levels are correlated with the global confinement time; this is not the case for the edge density fluctuations. Present measurements in the supershot regime indicate that the characteristic properties of the long-wavelength density fluctuations are similar to those in the L-mode regime. Reflectometry measurements are under way in most of the major experiments. They should be able to identify the long-wavelength fluctuations (MAZZUCATO, 1991). At present, there is some controversy about the interpretation of the reflectometry results.

Confronted with these experimental results, the first question we can ask is what is the underlying cause for the long-scale-length fluctuations? There are two different and broad lines of thought in interpreting fluctuation and transport experiments. On one hand,

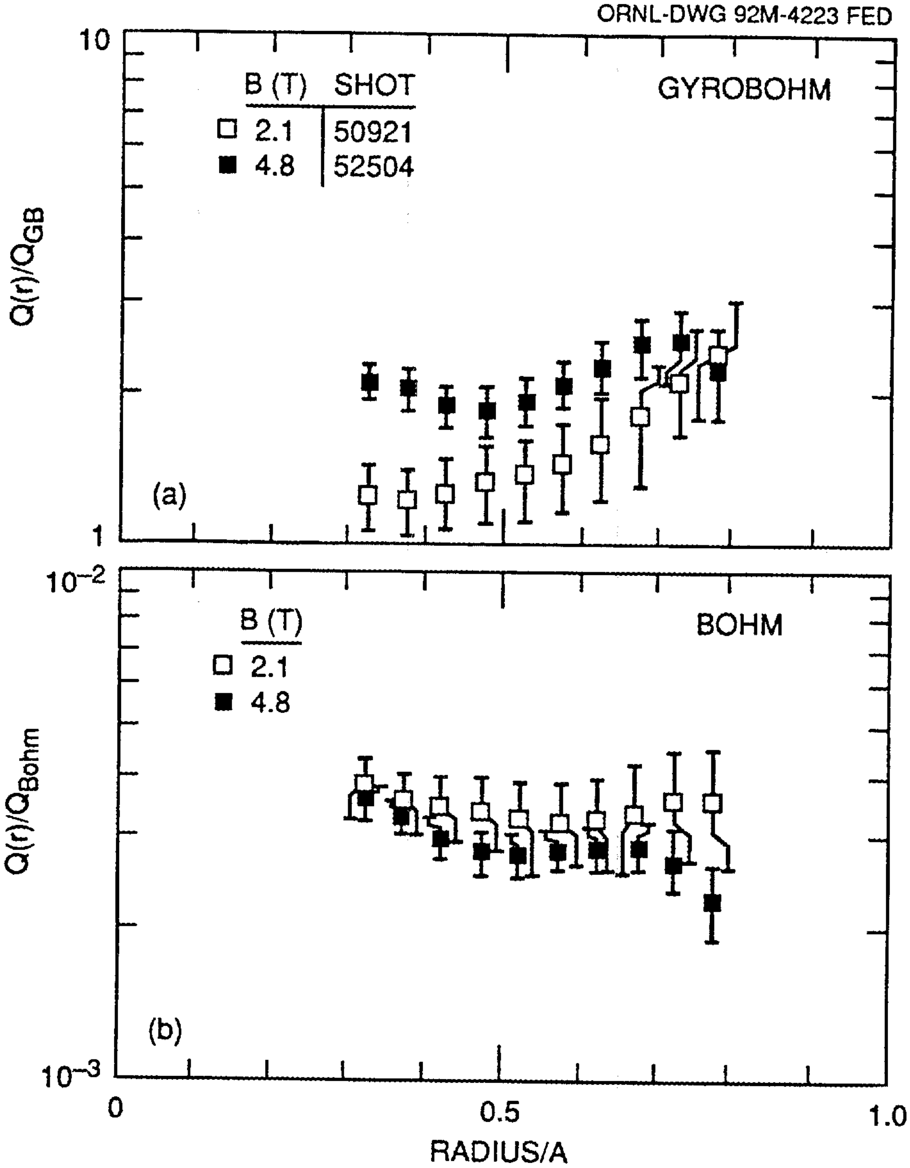

Fig. 1. Comparison of normalized fluxes from two dimensionally similar discharges in TFTR. When the data are normalized to the correct scaling law, the spread of data points should be minimal. These data clearly favor Bohm scaling (PERKINS, 1992).

several theoretical (KADOMTSEV, 1991; HEGNA, 1991) and semiempirical (REBUT, 1986 and 1989) models are based solely on magnetic turbulence-induced transport; on the other hand, most of the theoretical turbulence studies are focused on electrostatic turbulence. The magnetic-island-based transport models offer a simple and direct interpretation to the electron temperature measurements, although there are alternative interpretations (discussed below). The experimental results in tokamaks in which $\chi_i \cong \chi_\varphi \cong \chi_e \geq D_e \cong D_z$ call into question models of tokamak heat transport based on stochastic magnetic fields (GOLDSTON, 1989; WAGNER, 1992). These results would be more consistent with

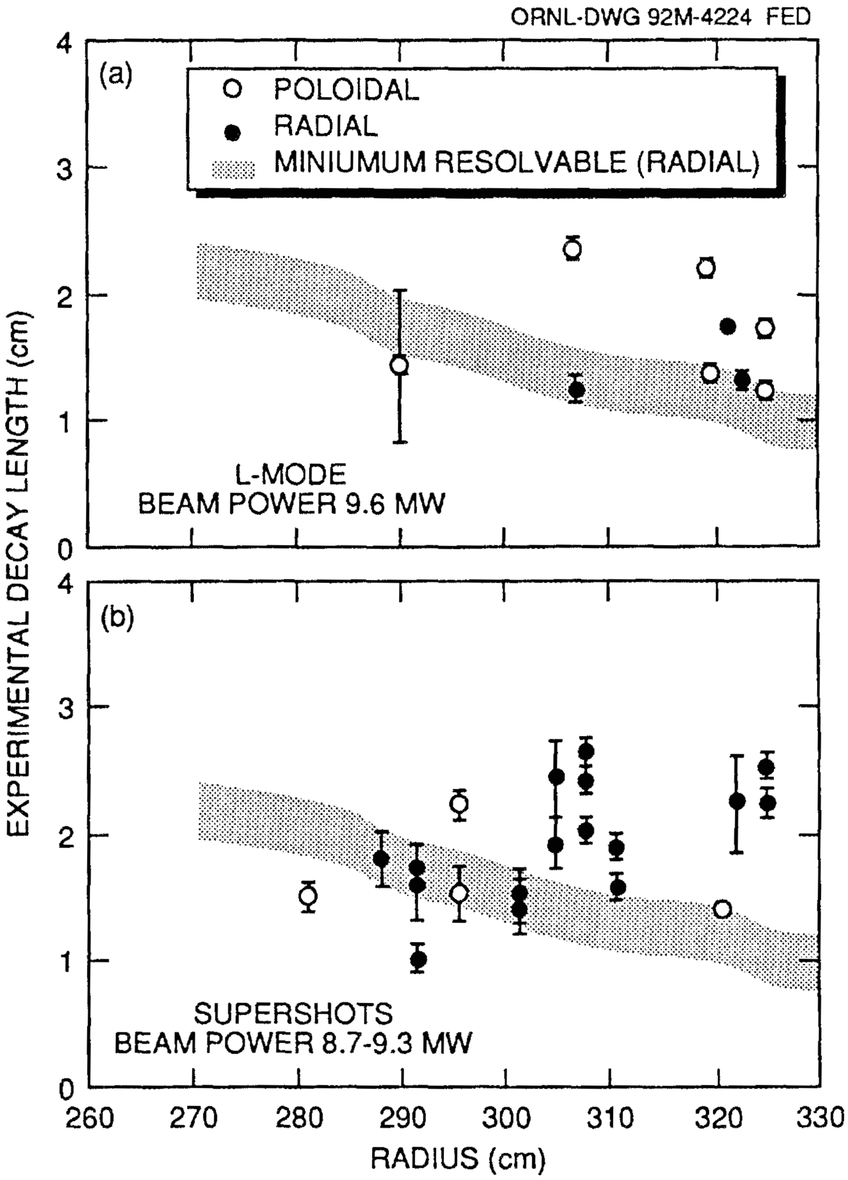

Fig. 2. Correlation lengths as a function of radius for L-mode (top) and supershot (bottom) discharges in TFTR (FONCK, 1992).

transport predictions based on $\vec{E} \times \vec{B}$ turbulence. Therefore, a critical issue to be resolved is the relative roles of magnetic and electrostatic turbulence in plasma transport. Direct measurement of magnetic fluctuations in the plasma core remains a major challenge. The use of the heavy ion beam probe (HIBP) for the measurement of magnetic fluctuations is being explored on the Texas Experimental Tokamak (TEXT) (CROWLEY, 1990). There are also indirect methods of measuring the magnetically induced transport, such as the use of runaway electrons (KWON, 1988; MYRA, 1991). The interpretation of the results from experiments based on runaway electrons is not simple and requires a refinement of the theoretical models for particle diffusion in stochastic magnetic fields. It would be interesting to see these techniques applied in more experiments. In particular, they could be tested in stellarators, where the magnetic field structure can be measured with precision and modified with external controls.

Recent analytical and numerical (CARRERAS, 1992a) work on electron drift wave turbulence reveals that low-q resonant surfaces may support modes that self-bind to inhibit the magnetic and flow shear damping effects. This would cause spatial intermittency in the turbulence, with large fluctuation levels at the low-q resonances and lower levels in between (Fig. 3). At these resonances, the spectrum peaks at very long wavelength and the radial and poloidal correlation lengths are different, while between resonances the spectrum is more isotropic. This spatial intermittency in the turbulence may be the reason for the choppy electron temperature profiles. This offers an alternative explanation for the presence of magnetic islands in the plasma and allows for an interpretation of the experimental data based on electrostatic turbulence models.

The duality in theoretical approaches to tokamak transport is also present in the transport modeling efforts. Transport modeling based on critical ∇T_e (TARONI, 1991) has been successful in explaining many features of the experimental data. Also, we have seen progress in modeling tokamak discharges based on theoretically derived transport models (SINGER, 1988; REDI, 1991; BATEMAN, 1992). These calculations combine the effect of multiple instabilities over their different regimes of applicability. Considering the difficulty of this task, present results are encouraging.

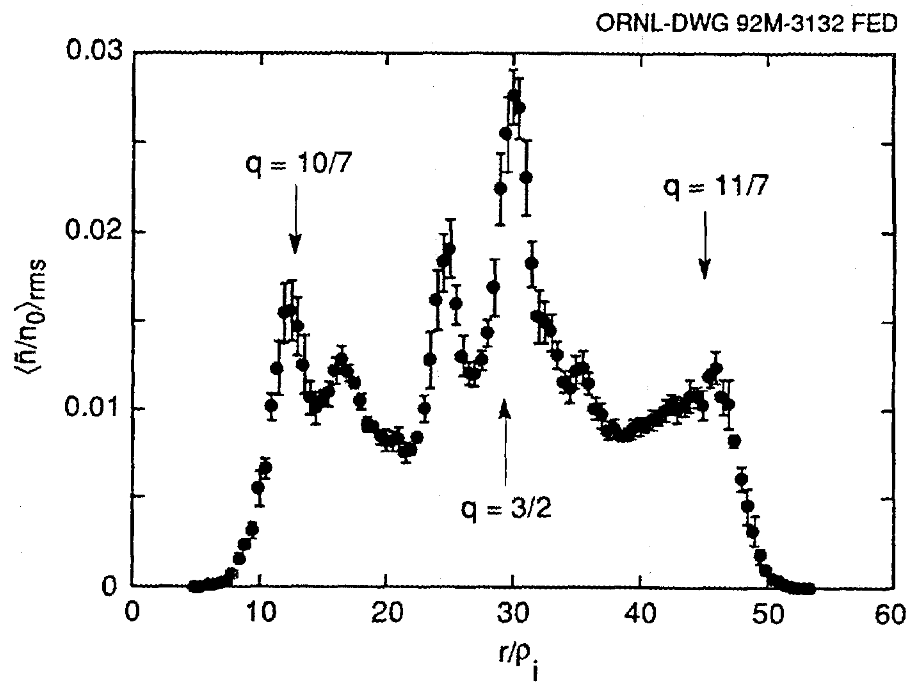

Fig. 3. Saturation level of density fluctuations for long-wavelength drift wave turbulence, showing peaks associated with the position of the low-q resonance. The numerical results have been time averaged, and the error bars reflect the variation of fluctuation levels in the time interval considered.

3. PLASMA CORE FLUCTUATIONS AND TRANSPORT: THEORY

Electrostatic turbulence can be the main cause of the plasma fluctuations and transport. In low-collisionality plasmas, trapped-ion instabilities (KADOMTSEV, 1970; TANG, 1978) are a likely candidate to explain the long-wavelength fluctuations. Analyses of trapped-ion modes were popular in the 1970s. These instabilities were supposed to induce a particularly unfavorable temperature dependence of the diffusivities (COHEN, 1976) with condensation of the turbulence spectrum in the long wavelengths. As a consequence, the predicted transport losses were catastrophic, with Bohm-like scaling (SAISON, 1978). When high ion temperatures were achieved in the Princeton Large Torus (PLT) (EUBANK, 1979) without this deleterious confinement, the study of trapped-ion instabilities came to an impasse. Motivated by the recent experimental results, researchers have revisited the theory of trapped-ion turbulence.

In one dimension, the radial structure of the trapped-ion modes is localized by magnetic shear. The strong ion Landau damping at the resonant surfaces forces the mode to localize itself halfway between adjacent surfaces (GLADD, 1973). In toroidal geometry, this eigenfunction structure can change, acquiring a ballooning structure in the poloidal direction. Recently, full two-dimensional (2-D) calculations (TANG, 1992) have been performed for realistic TFTR parameters and low-wavelength modes. It has been found that the shear localization is not strong enough and the modes spread over many rational surfaces. These modes are radially localized by the equilibrium gradients. In this case, the relevant radial width of the trapped-ion mode is an order of magnitude larger than the ion gyroradius. These radial scale lengths are consistent with experimental measurements.

Significant conceptual changes have occurred in the turbulence theory of the trapped-ion instability (DIAMOND, 1990; BIGLARI, 1991). Here, to explain some of these changes, I consider dissipative trapped-ion convective cells. In slab geometry, the nonlinear evolution of these instabilities can be described by a 2-D fluid equation (KADOMTSEV, 1971),

$$\frac{\partial \tilde{n}_i}{\partial t} + \bar{V}_* \frac{\partial \tilde{n}_i}{\partial y} + \frac{\nu_i}{\varepsilon} \tilde{n}_i + D_{i0} \frac{\partial^2 \tilde{n}_i}{\partial y^2} - \frac{L_n D_{i0}}{\sqrt{\varepsilon}} \left[\nabla_\perp \left(\frac{\partial \tilde{n}_i}{\partial y} \right) \times \hat{z} \right] \cdot \nabla_\perp \tilde{n}_i = 0 \ . \quad (1)$$

Here $\tilde{n}_i$ is the normalized trapped-ion density perturbation, $\varepsilon = r/R$ is the inverse aspect ratio, $D_{i0} = \varepsilon \bar{V}_*^2 (1 + 3\eta_e/2) / \nu_e$, $\bar{V}_* = \sqrt{\varepsilon} V_{T_i}^* / [1 + (1/\tau)]$, and $V_{T_i}^* = \varepsilon^{1/2} k_y \rho_i V_{T_i} / L_n$, $\tau = T_e/T_i$, with ρ_i the ion Larmor radius and V_{T_i} the ion thermal velocity. This equation leads to the linear dispersion relation,

$$\omega = \frac{\sqrt{\varepsilon}\omega_{*e}}{1+\tau} - i \frac{\nu_i}{\varepsilon} + i k_y^2 D_{i0} \ . \quad (2)$$

This dispersion relation is valid in the fluid limit, and it shows that the trapped-ion modes are destabilized by electron collisions and stabilized by ion collisions. In a complete linear stability analysis of these instabilities, other kinetic effects, such as Landau damping by circulating ions, should be included. In the study of the basic nonlinear dynamics of the long-wavelength dissipative trapped-ion fluctuations, however, Eq. (1) is adequate. The analysis of Eq. (1) (DIAMOND, 1990) shows that the dominant nonlinear mechanism is strong turbulence mode coupling and that this equation can be solved using standard strong turbulence renormalization methods. Even if Eq. (1) is essentially 2-D, there is only one conserved quantity, instead of two as in the Hasegawa-Mima equation (HASEGAWA, 1977), and, as a consequence, there is no dual cascade. The spectral energy transfer is to the small scales, and no long-wavelength condensation of fluctuation energy is possible. The trapped-ion instabilities can grow to large fluctuation amplitude. Their fluctuation level at saturation is essentially given by the mixing length approximation, $\tilde{n}_i \approx \Delta/L_n$. In the case of eigenfunctions localized by the magnetic shear, the mixing length is $\Delta \approx k_r^{-1} \approx \left(\hat{S}k_\theta\right)^{-1}$, where $\hat{S} = \left(r/q^2\right)\left(dq/dr\right)$ is the magnetic shear parameter. Since the fluctuations have slow radial motion, the transport level is not catastrophic and is comparable to the trapped-electron-induced turbulence. The predicted transport coefficients are

$$\chi_i \approx \chi_e \approx \frac{3}{2} D \approx \frac{3}{8} \frac{\varepsilon^2 \rho_i^2 V_i^2}{\nu_e L_n^2 \hat{S}^2} , \qquad (3)$$

and they scale like gyro-Bohm. The scaling of χ with electron temperature given by Eq. (3) is $\chi \propto T_e^{7/2}$. Although this dependence is rather unfavorable, it is not far from the one experimentally determined in the density modulation experiments (EFTHIMION, 1991), $\chi \propto T_e^{5/2}$. The turbulence regime in which the eigenfunction is localized by the equilibrium profile must be investigated. In this regime, Bohm-like scaling is probably recovered.

In higher collisionality regimes, long-wavelength electron drift waves could be the mechanism responsible for the transport losses. To study the nonlinear behavior of these instabilities, it is also useful to go to the fluid limit. For long-wavelength dissipative trapped-electron modes, an equation similar to Eq. (1) can be derived (CARRERAS, 1992a). In this regime, the trapped-electron response is laminar and the ions can be treated as a fluid. The equation governing long-wavelength dissipative trapped-electron turbulence is

$$\frac{\partial \tilde{n}_i}{\partial t} - \rho_s^2 \frac{\partial \nabla_\perp^2 \tilde{n}_i}{\partial t} + V_{*n} \frac{\partial \tilde{n}_i}{\partial y} + D_0 \frac{\partial^2 \tilde{n}_i}{\partial y^2} - \frac{c_s^2}{\nu_i} \nabla_\parallel^2 \tilde{n}_i$$
$$- L_n D_0 \left[\nabla_\perp\left(\frac{\partial \tilde{n}_i}{\partial y}\right) \times \hat{z}\right] \cdot \nabla_\perp \tilde{n}_i + \rho_s c_s (\nabla_\perp \tilde{n}_i \times \hat{z}) \cdot \nabla_\perp\left(\rho_s^2 \nabla_\perp^2 \tilde{n}_i\right) = 0 \ . \qquad (4)$$

In this equation, the ion density perturbation has been normalized to its equilibrium value, n_0. The first and third terms in Eq. (4) represent ion density advection, the sixth term is the $\vec{E} \times \vec{B}$ nonlinearity, and the seventh term is the polarization drift nonlinearity. The instability driving term is the fourth term, with $D_0 = \left[3\varepsilon^{3/2}(\rho_s c_s)^2\right] / (L_T L_n \nu_e)$. This term introduces an effective $i\delta$ drive. The fifth term in Eq. (4) refers to the parallel flow damping.

The $\vec{E} \times \vec{B}$ nonlinearity is the result of including the nonadiabatic electron contribution. This term qualitatively changes the character of the Hasegawa-Mima equation, so that enstrophy is no longer conserved by Eq. (4). This equation has only one conserved quantity, and as a consequence there is no dual cascade. The energy spectrum for both equations is greatly changed from the Hasegawa-Mima spectrum. The spectral properties have been investigated analytically (LIANG, 1992) and numerically (NEWMAN, 1992) in the 2-D limit. The character of each nonlinearity can be investigated by pulse propagation in k space. The polarization drift nonlinearity causes a slow, dual-cascade-type propagation. The $\vec{E} \times \vec{B}$ nonlinearity causes a fast initial propagation to the high-k range of the spectrum (nonlocal propagation), followed by a slow inverse cascade. The saturated spectrum depends on the dominant nonlinearity, with a flatter spectrum in the $(\vec{E} \times \vec{B})$ dominated region and a more sloping spectrum in the polarization drift nonlinearity dominated region. There is a very marked frequency upshift in the region where both nonlinearities are important. This frequency shift could have some relevance to present fluctuation measurements.

Two more aspects of the long-wavelength turbulence are worth considering. First, it can drive short-wavelength turbulence by the transfer of energy to high k. Therefore, it is important to include this source of energy in the short-wavelength turbulence calculations. A second point is that long wavelengths can modulate the short-wavelength turbulence (BALK, 1990; DIAMOND, 1990). This modulation can be responsible for some of the nonlocal effects observed in fluctuation (SING, 1991) and transport (LUCE, 1991) studies. In DIII-D, the inward heat flux cannot be explained by purely diffusive models, including those based on a critical temperature gradient. The experimental observations of nonlocal effects are mainly in experiments with electron cyclotron heating (ECH), and more work is needed to confirm the present results and to understand their consequences.

In trying to understand the plasma core confinement, a great deal of theoretical and computational activity has been concentrated on ion-temperature-gradient-driven turbulence models. Opinion based on experimental comparison of the relevance of such models has been oscillating (ZARNSTORFF, 1990, 1991). The first analytical results for χ_i were derived for η_i larger than the stability threshold where a fluid approximation could be applied. This results in values for χ_i that are too high compared with the values obtained in the experiment. The fact that η_i instabilities can lead to such high levels of losses suggests that a marginal stability condition could constrain the profiles (BIGLARI, 1989). The determination of the marginal stability requires the use of kinetic theory in full toroidal geometry. Analytical work has progressed in refining the calculation of stability thresholds (ROMANELLI, 1989; HAHM, 1989; XU, 1992). The nonlinear analytical theory is not yet developed enough to allow the desirable detailed comparisons. The combined difficulties of including kinetic effects and realistic geometry make the analytical nonlinear problem close to intractable. Systematic numerical calculations are needed.

Recently, a more detailed comparison of the TFTR supershot profile modification experiment with toroidal η_i stability theory (HORTON, 1992) has resolved some of the apparent contradictions between theory and experiment, at least at the plasma core. The development of gyrofluid models with Landau closure (HAMMETT, 1990) has extended the computational capabilities for studying this type of turbulence with fluid models (WALTZ, 1991). Gyrokinetic calculations are also under way (COHEN, 1991a; PARKER, 1991).

4. PLASMA EDGE FLUCTUATIONS AND TRANSPORT

At the plasma edge in Ohmic-type discharges, a velocity shear layer is present. This velocity shear layer determines the characteristic edge confinement radius (RITZ, 1989) and provides a useful way of comparing results from different magnetic confinement devices. Around the velocity shear layer, the turbulence fluctuation levels are high (20% to 60%). In this region, tokamaks and stellarators show similar fluctuation levels and properties (WOOTTON, 1992b), and the particle edge transport is consistent with the fluxes calculated using the measured electrostatic fluctuations. In the Madison Symmetric Torus (MST), systematic measurements of fluctuation-induced fluxes are being carried out. Apart from the usual electrostatic particle and energy fluxes (REMPEL, 1991), the particle flux induced by magnetic fluctuations has been measured (SHEN, 1992), and the measurement of electron energy flux induced by magnetic fluctuations is under way. These measurements can greatly improve our understanding of the edge transport mechanisms.

The universal character of the edge turbulence eliminates turbulence models such as the rippling-mode-induced turbulence, which requires $E_{\|} \neq 0$. The high level of fluctuations is difficult to explain with only plasma drives. A nonlinear mechanism, like the one causing the self-sustainment of dissipative drift wave turbulence (SCOTT, 1990), could play a role in edge turbulence and should be further investigated in 3-D geometry. Atomic physics drives can lead to high fluctuation levels, and they have been used to reproduce some of the properties of Ohmic edge plasmas (LEBOEUF, 1991). Radiation and ionization can drive instabilities, and they could be responsible for the edge turbulence (WARE, 1992b). This could provide the link between the modification of edge confinement properties and the control of neutral gas and impurities. This edge fluctuation model is rather complex, and a detailed determination of these atomic physics drives is needed to make it a predictive model. The presence of limiters modifies the turbulence by introducing a geometrical dependence of the ionization source (MOROZOV, 1991; SÜNDER, 1991) and/or by introducing a new instability mechanism, the gradient of the electron temperature at the limiter (COHEN, 1991b). These effects have not yet been incorporated into a detailed edge turbulence model.

Measurements at the plasma edge in the Continuous Current Tokamak (CCT) with a 2-D array of probes show the existence of complex, large flow structures (TYNAN, 1991). It is not clear whether these structures exist in all tokamaks or occur in only a few devices. In any case, the CCT edge flow measurements underline the importance of more detailed measurement of the fluctuations in the study of edge plasma turbulence.

The equilibrium transport modeling of the plasma edge at the shadow of the limiter has made a great deal of progress in incorporating the magnetic geometry. Good coupling has not yet been obtained between these studies and edge turbulence modeling. Bringing these two approaches together in the description of the plasma edge is a challenge for the theorists and modelers.

In auxiliary heated tokamaks and stellarators, and further inside the plasma where the temperature is too high for the atomic drives to be operative but where fluctuations are still relatively high (1% to 10%), other turbulence mechanisms must be acting. In L-mode discharges, the resistive ballooning turbulence (resistive interchange turbulence in stellarators) and/or ion-temperature-gradient-driven turbulence are possible candidates. Equilibrium transport modeling of TFTR discharges (REDI, 1991; BATEMAN, 1992) identifies the resistive ballooning-induced transport, because of its magnetic shear and q dependence, as a possible mechanism to explain the current scaling of the global confinement. One interesting property of transport models based on resistive pressure-gradient-driven turbulence (CARRERAS, 1989) is that the radial scale length of the magnetic fluctuations, Δ_M, is a hybrid of the electrostatic mixing length, Δ_Φ, and global scales, $\Delta_M \approx \sqrt{\Delta_\Phi r/m}$. Therefore, these models lead to a transport scaling that is not the gyro-Bohm scaling. The resistive pressure-gradient-driven turbulence model has been extended to lower collisionality (KWON, 1990), introducing the bootstrap current drive and a plateau-type viscosity term. By coupling the resistive ballooning turbulence with a poloidal shear flow (DRAKE, 1991), the resistive pressure-gradient-driven turbulence has been advanced as a possible mechanism for the L-H transition. This is discussed in Sect. 5.

The first current ramp experiments (ZARNSTORFF, 1990) raised serious questions about the use of these local diffusion mechanisms to explain the current scaling. After two years of experiments in several machines, there is agreement for all experiments on the effect of the current profile on the global confinement time. Specifically, τ_E increases when l_i increases. Transport analysis finds that changes in confinement can be explained with a local heat diffusivity that depends on the magnetic shear, although it is not yet clear whether all time scales involved in these experiments are explained. For DIII-D results, the average heat diffusivity increases linearly with the shear length. For JET results, it should be proportional to $q^2/\sqrt{S}$. The TFTR measurement allowed a separation of the electron and ion channels. It was found that there was no dependence on shear for the electrons and a linear dependence on the shear length for the ion heat diffusivity. The critical temperature gradient model adequately explains the JET experiments but does not agree with TFTR data (ZARNSTORFF, 1992).

5. TURBULENT FLUCTUATIONS AND POLOIDAL FLOWS

In the last few years, the relationships between the radial electric field and plasma edge fluctuations, and their joint effect on transport, have attracted a great deal of attention. The main motivation is the understanding of the L-H transition (WAGNER, 1982). After the causal relation between the radial electric field and the L-H transition was first suggested (ITOH, 1988), it was followed by more detailed models (SHAING, 1988) based on a two-step process: (1) at a certain level of injected power in a tokamak, the edge particle losses create or modify the radial electric field; and (2) this electric field is then responsible for the reduction of the fluctuation level and transport. These models did not consider in detail the dynamics of edge turbulence suppression. It had been shown (CHIUEH, 1986) that a poloidal shear flow in a plasma confined by a sheared magnetic field has, in general, a strong stabilizing effect. In general, a shear poloidal flow $\left[V_\theta'(x) = V_\theta' x\right]$ introduces an asymmetry into the eigenfunction. This asymmetry causes modes with different radial wave numbers (ℓ) to couple. When, in the absence of flow, the high-ℓ modes are damped, the presence of the shear flow stabilizes. The shear flow is destabilizing when the high-ℓ modes are more unstable than the lowest-ℓ modes. To understand the effect of the shear flow on transport, the question is how the poloidal shear flow affects the nonlinear stability and turbulence levels. A general scaling model (BIGLARI, 1990) was used to study the effect of shear flow on turbulence. This model showed that, in the presence of a shear flow, the turbulence decorrelation time, τ_c, is a hybrid time scale of the shearing time scale, $\tau_s = 1/\left(k_\theta V' \Delta_\theta\right)$, and the diffusive time scale, $\tau_D = \Delta^2/D$. This decorrelation time is $1/\tau_c \cong \left(k_y^2 V_\theta'^2 D\right)^{1/3} = 1/\tau_D^{1/3}\tau_s^{2/3}$. When the shearing effect dominates, $\tau_s < \tau_D$, the effective turbulence decorrelation time is reduced. As a consequence, fluctuation levels should be reduced. In recent years, several turbulence models have been used to study the effects of shear flow on turbulence in a self-consistent way. The numerical and analytical results from these studies raise questions about the simple scaling model because the stabilizing effects, which are always confirmed in the linear instability regime, do not always appear in the nonlinear regime. Turbulent suppression by shear flow has been confirmed in the numerical calculations of ion-temperature-gradient-driven turbulence (WALTZ, 1991; HAMAGUCHI, 1992), high-k drift-resistive ballooning turbulence (DRAKE, 1992b), and drift-thermal turbulence (WARE, 1992a). However, no nonlinear suppression of turbulence by pure shear flow, $V_\theta' \neq 0$ and $V_\theta'' \neq 0$, has been observed for long-wavelength drift wave turbulence (CARRERAS, 1992a) or resistive interchange turbulence (CARRERAS, 1992b). In these cases, the single-helicity effects at the low-q resonances are important, nonlinearly the instabilities self-bind, the radial shift of the eigenfunction is reduced, and the shear stabilization effects are inhibited. In the case of a flow with curvature $\left[V_\theta(x) = V_\theta'' x^2/2\right]$, the linear stabilization is through the change in the eigenfunction width. The flow curvature, which is naturally generated by diamagnetic effects, seems to be more effective in turbulence suppression for these latter examples.

The ideas of turbulence suppression by poloidal shear flow as a model for the L-H transition attracted a great deal of attention after the observations in DIII-D of the correlation between a jump in the measured poloidal rotation velocity and the transition (GROEBNER, 1990) and the demonstration in CCT that the transition to an improved confinement regime could be externally triggered by the injection of electrons into the plasma, creating a radial electric field (TAYLOR, 1989). Similar results have been obtained in the TEXTOR tokamak (WEYNANTS, 1990). Experimental work at DIII-D has proceeded with continuous improvement in the measurements and their resolution. Within the time resolution of present experiments, the increase in the poloidal shear flow occurs simultaneously with the decrease in plasma edge fluctuation level and with the improvement in confinement, the L-H transition. During the H-mode, the edge poloidal velocity, V_θ, as a function of the radius has a minimum (BURRELL, 1991). More details on the present experimental status of the L-H transition can be found in a review paper on this topic (BURRELL, 1992).

Let us now turn to the origin of the poloidal flow and its radial localization at the plasma edge. There are several possible sources for the generation of this poloidal shear flow. One possible explanation is the ion orbit loss at the plasma edge (SHAING, 1992a). In this case, the radial scale length is given by the banana width. Another suggested mechanism for the increase in poloidal rotation is the poloidal asymmetry in the particle anomalous diffusion (HASSAM, 1991). An alternative or complementary explanation is the modification of the flow profile by the plasma turbulence via the Reynolds stress (CARRERAS, 1991, DIAMOND, 1991a). This latter mechanism has been invoked in fluid dynamics to explain the differential rotation of the solar atmosphere (RÜDIGER, 1989). It implies a strong coupling between turbulent fluctuations and averaged flows. The turbulent fluctuations modify the mean poloidal flow profile, which simultaneously controls the level of fluctuations. Therefore, self-consistent calculations of plasma turbulence in the presence of flows are needed to identify the mechanism of confinement improvement. These calculations must be done for each particular turbulence model, because the flow profile modification depends on the radial structure of the turbulence.

The poloidal flow profile evolution equation is derived by taking the flux surface average of the momentum balance equation:

$$\frac{\partial \langle V_\theta \rangle}{\partial t} = -\frac{\partial}{\partial r}\left(\left\langle \tilde{V}_r \tilde{V}_\theta \right\rangle - \frac{1}{\rho_m \mu_0}\left\langle \tilde{B}_r \tilde{B}_\theta \right\rangle\right) . \qquad (5)$$

Here, the angular brackets, $\langle\ \rangle$, indicate the poloidal and the toroidal angle average over a magnetic flux surface. No explicit form for the damping has been included in Eq. (5). The nonlinear terms in the momentum balance equation generate the nondiagonal $r\theta$ terms of the Reynolds stress tensor $S_{ij} \equiv \left\langle \tilde{V}_i \tilde{V}_j \right\rangle - \left\langle \tilde{B}_i \tilde{B}_j \right\rangle / \rho_m \mu_0$. The first term results from the convective nonlinearity and the second term from the magnetic nonlinearity in the parallel derivative of the parallel current density. In the case of electromagnetic turbulence, these terms tend to cancel each other (CRADDOCK, 1991). Therefore, it is important to accurately calculate both contributions. The Reynolds stress does not contribute a net momentum source, as can be seen by integrating Eq. (5) over the radius. The Reynolds stress does not create momentum, but it redistributes momentum along the radial direction.

For an effective modification of the average poloidal flow profile, the Reynolds stress tensor must be nonzero, $S_{r\theta} \neq 0$. This requires a symmetry-breaking effect on the advection and the radial inhomogeneity of the turbulence. The latter sets the radial scale length of the shear flow, and it is of the order of the radial width of the underlying instability, that is, a few times ρ_s. This mechanism, because of its nonlinear character, is expected to be dominant at the edge, where the fluctuation levels are high. The symmetry breaking can be produced by several mechanisms. One example is the existence of an initial "seed" flow with radial structure, that is, $V_0' \neq 0$ and/or $V_0'' \neq 0$ (DRAKE, 1992a). In this case and for the mode represented by Eq. (4), the flow profile modification can be written (DIAMOND, 1992a) as

$$\frac{\partial}{\partial t} \langle V_\theta'' \rangle_{x=0} - \mu \langle V_\theta'' \rangle_{x=0} = \frac{c_s^2 \rho_s^2}{L_n D_0 \Delta} \left| \frac{\tilde{n}}{n_0} \right|^2 V_0'' \, . \quad (6)$$

This equation indicates that the symmetry-breaking effect introduced by V_0'' leads to an amplification of the flow curvature. This is a dynamo-type instability, an effect similar to the anisotropic kinetic alpha instability (GALANTI, 1991). The instability is controlled by the fluctuation level. An analogous equation has been derived for $\langle V_\theta' \rangle_{x=0}$. Another symmetry-breaking effect is the radial propagation induced by electron diamagnetic rotation (HASEGAWA, 1987; CARRERAS, 1991). There is evidence of radial inhomogeneity of the turbulence at the low-q surface and at the plasma edge (Fig. 4).

Another important ingredient in a model for the L-H transition is the existence of bifurcated solutions. The bifurcation can be caused by different nonlinearities in the model. Several particular nonlinearities have been studied.

The first nonlinearity considered was the one in the magnetic pumping dissipation, which is a nonlinear function of the poloidal velocity for large ion poloidal rotation; when balanced with the ion orbit loss it leads to a bifurcated solution (SHAING, 1989). This model predicts high poloidal rotation velocities that lead to shock formation (SHAING, 1992b) in agreement with some of the experimental observations in CCT (TAYLOR, 1992).

Another possible source for bifurcation is in the basic transport equations. The turbulence suppression by shear flow induces a nonlinear dependence in the anomalous heat diffusion coefficients on the poloidal shear velocity. For high shear flow, bifurcated solutions have been found (HINTON, 1990).

Finally, the system of equations for flow profile modification via Reynolds stress and for the turbulence dynamics in the presence of flows is intrinsically nonlinear and can lead to multiple steady-state turbulence solutions with different levels of fluctuations and shear flow. Taking into account the flow curvature only, DIAMOND (1991b) used

Eq. (6); it is analogous for $\langle V_\theta' \rangle_{x=0}$, and the condition for nonlinear saturation of the long-wavelength drift waves in the presence of flows,

$$0 = \frac{\gamma}{\omega_R} \equiv \frac{\omega_{*e}}{\nu_{eff}} \left(\frac{3}{2} \eta_e - 1 - \frac{k_y \langle V_\theta'' \rangle_{x=0} W^2}{\omega_R} \right) \frac{W^2}{4\rho_s^2} \frac{k_y \langle V_\theta' \rangle_{x=0}^2 W^2}{\omega^2 d} - \beta d \; , \qquad (7)$$

as a simple model that includes the basic nonlinearities (DIAMOND, 1991b). Here d is the nonlinear diffusivity normalized to $\rho_s^2 \omega_s$. These three equations lead to bifurcated solutions for the level of fluctuations $(\tilde{n}/n_0)$. For low values of $(\tilde{n}/n_0)$, the flow curvature $\langle V_\theta'' \rangle$ dominates, but for high $(\tilde{n}/n_0)$, the shear $\langle V_\theta' \rangle$ is dominant. A numerical solution of resistive pressure-gradient-driven turbulence showing a transition from low to high levels of fluctuations associated with high and low values of V_0'' is shown in Fig. 4.

There is not yet an L-H transition model that incorporates all needed ingredients (poloidal flow generation, profile modification, turbulence suppression, and bifurcated solution) in a self-consistent way and for a realistic geometry. However, at present, most of the components for such a model seem to be under detailed study.

ORNL-DWG 92M-3133 FED

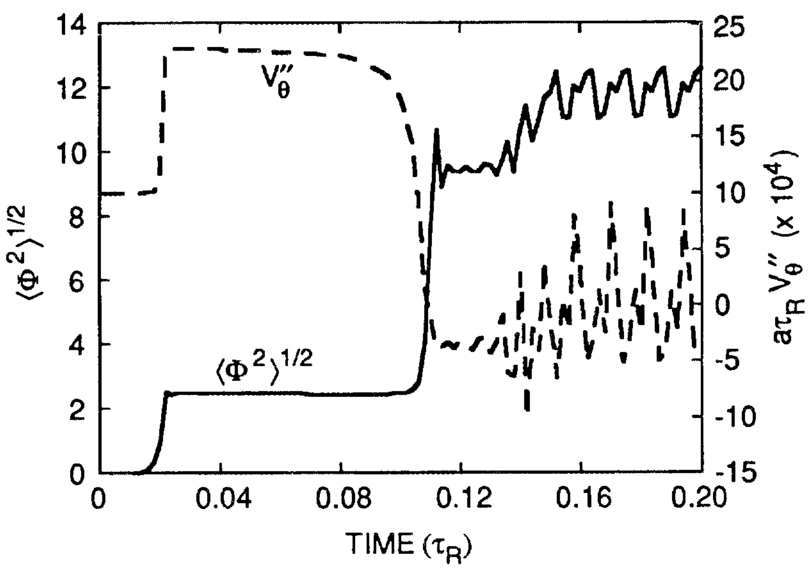

Fig. 4. Transition from a low to a high fluctuation level associated with high and low values of V_θ'', respectively. Numerical results are based on the resistive pressure-gradient-driven turbulence model.

6. COMPARISON OF TOKAMAK AND STELLARATOR TRANSPORT

The present generation of stellarator devices is characterized by average plasma minor radii of 10 cm to 27 cm. In this size plasma, transport studies can be carried out without being dominated by edge plasma effects. The energy confinement time in these stellarators is the same as in tokamaks of the same minor radius. However, there are some differences in the underlying transport mechanism that lead to somewhat different transport scalings and properties of the equilibrium profiles.

Most of the stellarator discharges have L-mode-type behavior. However, in contrast to tokamaks, the local transport scaling seems to be closer to gyro-Bohm than to Bohm, as has been shown in the Advanced Toroidal Facility (ATF) (MURAKAMI, 1992), in the Compact Helical System (CHS) (MATSUOKA, 1992), and in the Wendelstein VII–Advanced Stellarator (WVII-AS) (WAGNER, 1992). Therefore, the transport scaling in stellarators is somewhat more optimistic than L-mode scaling in tokamaks. This is reflected in a positive scaling with density, which is absent in tokamaks and compensates for the negative power scaling. The absence of a density limit in stellarators makes this compensation significant. In dimensionless parameters, modulation experiments in ATF give $\tau_E \propto \Omega_i^{-1}\rho_s^{-3}\nu_*^{-0.2}\beta^{0.4}$. That is, the scaling with β and collisionality is favorable. It is important to test this scaling at a significant β level. In WVII-AS, H-mode-type discharges have been obtained. The confinement improvement is still small when compared with the tokamak H-mode, about a 1.3 enhancement factor. However, these results are very recent, and a systematic study has not yet been carried out.

A second characteristic of the stellarator transport is the lack of the electron temperature profile resilience that has been observed in tokamaks. In WVII-AS and Heliotron-E, it has been shown that the electron temperature profile depends on the heat deposition profile. However, stellarators show a correlation between the electron temperature and density profiles. This correlation could be the result of a marginal stability condition to helically trapped electron modes (DOMINGUEZ, 1992).

7. CONCLUSIONS

Understanding the basic mechanisms of transport in toroidal confinement devices remains one of the more challenging scientific issues in magnetic confinement. The complexity of the problem makes progress slow. In recent years, we have seen a great increase in diagnostic capabilities. We have begun to get the benefits of these new diagnostics, but we can still expect a great deal more in the near future. In spite of the progress in diagnostics, further development is needed in some critical areas. This is particularly important in the area of magnetic fluctuations and their overall effect on transport.

Theory has been an active force for many years in the identification of instabilities and the study of their linear properties. A great deal remains to be done to advance the theory of nonlinear instabilities, turbulence, and the induced transport. Computational science is emerging as a powerful new approach in these studies. The next generation of computers will bring us closer to the capabilities needed for simulation of a confined plasma. Although another decade is probably needed to reach this goal, a great deal of understanding can be gained at present by solving simpler models that can help in sorting out the underlying physical mechanisms of the theoretical models.

ACKNOWLEDGMENTS

The author gratefully acknowledges useful discussions with and assistance in preparing this paper from J. D. Callen, P. H. Diamond, R. J. Fonck, K. Lackner, J.-N. Leboeuf, V. E. Lynch, M. Murakami, D. Newman, F. W. Perkins, K. Sidikman, D. Spong, P. W. Terry, F. Wagner, R. E. Waltz, and M. C. Zarnstorff.

REFERENCES

BALK, A. M., ZAKHAROV, V. E., and NAZARENKO, S. V. (1990), Sov. Phys. JETP **71**, 249.

BATEMAN, G. (1992), Phys. Fluids B **4**, 644.

BIGLARI, H., DIAMOND, P. H., ROSENBLUTH, M. N. (1989), Phys. Fluids B **1**, 109.

BIGLARI, H., DIAMOND, P. H., and TERRY, P. W. (1990), Phys. Fluids B **2**, 1.

BIGLARI, H., and DIAMOND, P. H. (1991), Phys. Fluids B **3**, 1797.

BRETZ, N., et al. (1988), Rev. Sci. Instrum. **59**, 1538.

BURRELL, K. H., and the L to H Transition Physics Task Group, (1991), Bull. Am. Phys. Soc. **36**, 2474.

BURRELL, K. H. (1992), "Physics of L to H Mode Transition," paper presented at the 19th European Physical Society Meeting on Controlled Fusion and Plasma Physics, Innsbruck, Austria, June 29–July 3, 1992.

CALLEN, J. D. (1990), Phys. Fluids B **2**, 2869, and papers that follow.

CALLEN, J. D. (1992), "Transport processes in magnetically confined plasmas," Phys. Fluids B **4**, accepted for publication.

CARRERAS, B. A., and DIAMOND, P. H. (1989), Phys. Fluids B **1**, 1011.

CARRERAS, B. A., GARCIA, L., LYNCH, V. E. (1991), Phys. Fluids B **3**, 1438.

CARRERAS, B. A., SIDIKMAN, K., DIAMOND, P. H., TERRY, P. W., and GARCIA, L. (1992a), Phys. Fluids B **4**, 3115.

CARRERAS, B. A., LYNCH, V. E., GARCIA, L., and DIAMOND, P. H. (1992b), "Resistive pressure-gradient-driven turbulence with self-consistent flow profile evolution," Oak Ridge National Laboratory Report ORNL/P-92/57995.

CHIUEH, T., TERRY, P. W., DIAMOND, P. H., and SEDLAK, J. E. (1986), Phys. Fluids **29**, 231.

COHEN, B. I., KROMMES, J. A., TANG, W. M., and ROSENBLUTH, M. N. (1976), Nucl. Fusion **16**, 971.

COHEN, B. I., WILLIAMS, T. J., DIMITS, A. M., and PEARLSTEIN, L. D. (1991a), Bull. Am. Phys. Soc. **36**, 2280.

COHEN, B. I., and XU, X. Q. (1991b), Bull. Am. Phys. Soc. **36**, 2279.

CORDEY, J. G. (1992), "Evidence for Local Diffusive Heat Flow in Tokamak," paper presented at the 19th European Physical Society Meeting on Controlled Fusion and Plasma Physics, Innsbruck, Austria, June 29–July 3, 1992.

CRADDOCK, G. G., and DIAMOND, P. H. (1991), Phys. Rev. Lett. **67**, 1535.

CROWLEY, T. P., ACETO, S. C., CONNOR, K. A., et al. (1990), Rev. Sci. Instrum. **61**, 2989.

DIAMOND, P. H., and BIGLARI, H. (1990), Phys. Rev. Lett. **65**, 2865.

DIAMOND, P. H., and KIM, Y. B. (1991a), Phys. Fluids B **3**, 1626.

DIAMOND, P. H. (1991b), Bull. Am. Phys. Soc. **36**, 2454.

DOMINGUEZ, N., CARRERAS, B. A., LYNCH, V. E., and DIAMOND, P. H. (1992), Phys. Fluids B **4** (in press).

DRAKE, J. F., GUZDAR, P. N., and DIMITS, A. M. (1991), Phys. Fluids B **3**, 1937.

DRAKE, J. F., FINN, J. M., GUZDAR, P. N., SHAPIRO, V., SHEVCHENKO, V., WAELBROECK, F., HASSAM, A. B., LIU, C. S., and SAGDEEV, R. (1992a), Phys. Fluids B **4**, 488.

DRAKE, J. F., et al. (1992b), "Edge Turbulence and Shear Flow Generation," paper presented at the Transport Task Force meeting, Oak Ridge, Tennessee.

EFTHIMION, P. C., MANSFIELD, D. K., STRATTON, B. C., SYNAKOWSKI, E., BHATTACHARJEE, A., et al. (1991), Phys. Rev. Lett. **66**, 421.

EUBANK, H., GOLDSTON, R. J., ARUNASALAM, V., BITTER, M., BOL, K., et al. (1979), in *Proceedings of the 7th International Conference on Plasma Physics and Controlled Nuclear Fusion Research 1978* (IAEA, Vienna), Vol. 1, p. 167.

FONCK, R. J., DUPERREX, P. A., and PAUL, S. F. (1990), Rev. Sci. Instrum. **61**, 3487.

FONCK, R. J., et al. (1992), "Fluctuation Measurements in the Plasma Interior," paper presented at the 19th European Physical Society Meeting on Controlled Fusion and Plasma Physics, Innsbruck, Austria, June 29–July 3, 1992.

GALANTI, B., and SULEN, P.-L. (1991), Phys. Fluids A **3**, 1778.

GLADD, N. T., and ROSS, D. W. (1973), Phys. Fluids **16**, 1706.

GOLDSTON, R. J., BIGLARI, H., HAMMETT, G. W., MEADE, D. M., YOSHIKAWA, S., and ZARNSTORFF, M. C. (1989), Bull. Am Phys. Soc. **34**, 1964.

GREK, B., JOHNSON, D., TAYLOR, G., and FREDRICKSON, E., (1991), Bull. Am. Phys. Soc. **36**, 2378.

GROEBNER, R. J., BURRELL, K. H., and SERAYDARIAN, R. P. (1990), Phys. Rev. Lett. **64**, 3015.

HAHM, T. S., TANG, W. M. (1989), Phys. Fluids B **1**, 1185.

HAMAGUCHI, S., and HORTON, W. (1992), Phys. Fluids B **4**, 319.

HAMMETT, G. W., and PERKINS, F. W. (1990), Phys. Rev. Lett. **64**, 3019.

HASEGAWA, A., and MIMA, K. (1977), Phys. Rev. Lett. **39**, 205.

HASEGAWA, A., and WAKATANI, M. (1987), Phys. Rev. Lett. **59**, 1581.

HASSAM, A. B., ANTONSEN, T. M., DRAKE, J. F., and LIU, C. S. (1991), Phys. Rev. Lett. **66**, 309.

HAWRYLUK, R. J., et al. (1991), Plasma Phys. Controlled Fusion **33**, 1509.

HEGNA, C. C., and CALLEN, J. D. (1991), "Interaction of bootstrap current driven magnetic islands," University of Wisconsin Report UW-CPTC 91-16.

HINTON, F. L. (1991), Phys. Fluids B **3**, 696.

HORTON, W., LINDBERG, D., KIM, J. Y., DONG, J. O., HAMMETT, G. W., SCOTT, S. D., AND ZARNSTORFF (1992), Phys. Fluids B **4**, 953.

ITOH, S. I. (1988), Phys. Rev. Lett. **60**, 2276.

KADOMTSEV, B. B. (1991), Nucl. Fusion **31**, 1301.

KADOMTSEV, B. B, and POGUTSE, O. P. (1970), in *Reviews of Plasma Physics*, edited by M. A. Leontovich (Consultants Bureau, New York), Vol. 5, 249.

KADOMTSEV, B. B., and POGUTSE, O. P. (1971), Nucl. Fusion **11**, 67.

KWON, O. J., DIAMOND, P. H., WAGNER, F., et al. (1988), Nucl. Fusion **28**, 1931.

KWON, O. J., DIAMOND, P. H., and BIGLARI, H. (1990), Phys. Fluids B **2**, 291.

LEBOEUF, J.-N., LEE, D. K., CARRERAS, B. A., et al. (1991), Phys. Fluids B **3**, 2291.

LIANG, Y.-M., DIAMOND, P. H., and WANG, X.-H. (1992), "Dual nonlinearity model of dissipative drift wave turbulence," Phys. Fluids B (to be published).

LUCE, T. C. (1991), Bull. Am Phys. Soc. **36**, 2349.

MATSUOKA, K. (1992), "Results from the CHS Device," paper presented at the 19th European Physical Society Meeting on Controlled Fusion and Plasma Physics, Innsbruck, Austria, June 29–July 3, 1992.

MAZZUCATO, E., and NAZIKIAN, R. (1991), Plasma Phys. Controlled Fusion **33**, 261.

MOROZOV, D. Kh., MOROZOV, N. N., SÜNDER, D. (1991), in *Proceedings of the 12th International Conference on Plasma Physics and Controlled Nuclear Fusion Research* (IAEA, Vienna) Vol. 2, 239.

MURAKAMI, M., et al. (1992), "Transport Studies Using Modulation of Dimensionless Parameters in the Advanced Toroidal Facility," paper presented at the 19th European Physical Society Meeting on Controlled Fusion and Plasma Physics, Innsbruck, Austria, June 29–July 3, 1992.

MYRA, J. R. (1991), Bull. Am. Phys. Soc. **36**, 2348 (1991).

NAVE, M. F., EDWARDS, A., HIRSH, K., HUGON, M., et al. (1992), Nucl. Fusion **32**, 825.

NEWMAN, D. E., TERRY, P. W., and DIAMOND, P. H. (1992), Phys Fluids B **4**, 599.

PARKER, S. E., and LEE, W. W. (1991), Bull. Am Phys. Soc. **36**, 2280.

PAUL, S. F., and FONCK, R. J. (1990), Rev. Sci. Instrum. **61**, 3497.

PERKINS, F. W. (1990), Bull. Am. Phys. Soc. **35**, 1918.

PERKINS, F. W., BARNES, C., JOHNSON, D. W., SCOTT, S. D., ZARNSTORFF, M. C., et al. (1992), Phys. Fluids B (to be published).

REBUT, P. H., and BRUSATI, M. (1986), Plasma Phys. Controlled Fusion **28**, 113.

REBUT, P. H., LALLIA, P. P., WATKINS, M. L., et al. (1989), in *Proceedings of the 12th International Conference on Plasma Physics and Controlled Nuclear Fusion Research 1988* (IAEA, Vienna) Vol. 2, 191.

REDI, M. H., and BATEMAN, G. (1991), Nucl. Fusion **31**, 547.

REMPEL, T. D., SPRAGINS, C. W., PRAGER, S. C., ASSADI, S., DEN HARTOG, D. J., HOKIN, S. (1991), Phys. Rev. Lett. **67**, 1438.

RITZ, Ch., LIN, H., RHODES, T. L., and WOOTTON, A. J. (1989), Phys. Rev. Lett. **62**, 1844.

RITZ, Ch., et al. (1991), in *Proceedings of the 13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna), Vol. 2, 589.

ROMANELLI, F. (1989), Phys. Fluids B **1**, 1018.

RÜDIGER, G. (1989), *Differential Rotation and Stellar Convection* (Gordon and Breach, New York).

SAISON, R., WIMMEL, H. K., and SARDEI, F. (1978), Plasma Phys. **20**, 1.

SCOTT, B. D. (1990), Phys. Rev. Lett. **65**, 3289.

SHAING, K. C., HOULBERG, W. A., and CRUME, E. C. (1988), Comments Plasma Phys. Controlled Fusion **12**, 69.

SHAING, K. C., and CRUME, E. C. (1989), Phys. Rev. Lett. **63**, 2369.

SHAING, K. C. (1992a), Phys. Fluids B **4**, 171.

SHAING, K. C., HAZELTINE, R. D., SANUKI, H. (1992b), Phys. Fluids B **4**, 404.

SHEN, W., DEXTER, R. N., and PRAGER, S. C. (1992), Phys. Rev. Lett. **68**, 1319.

SING, D. C. (1991), Bull. Am Phys. Soc. **36**, 2349.

SINGER, C. E. (1988), Comments Plasma Phys. Controlled Fusion **11**, 165.

SÜNDER, D., MOROZOV, D. Kh., and MOROZOV, N.N. (1991), Sov. J. Plasma Phys. **17**, 166.

TANG, W. M. (1978), Nucl. Fusion **18**, 1089.

TANG, W. M., and REWOLDT, G. (1991), Bull. Am. Phys. Soc. **36**, 2279.

TARONI, A., TIBONE, F., BALET, B., BOUCHER, D., CHRISTIANSEN, J. P., et al. (1991), in *Proceedings of the 13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna), Vol. 1, 93.

TAYLOR, R. J., et al. (1989), Phys. Rev. Lett. **63**, 2365.

TYNAN, G. R., BOEDO, J., CONN, R. W., et al. (1991), Bull. Am. Phys. Soc. **36**, 2500.

WAGNER, F., et al. (1982), Phys. Rev. Lett. **49**, 1408.

WAGNER, F. (1992), "Transport in Toroidal Devices: Experimentalist's View," paper presented at the 19th European Physical Society Meeting on Controlled Fusion and Plasma Physics, Innsbruck, Austria, June 29–July 3, 1992.

WALTZ, R. E., DEBOO, J. C., and ROSENBLUTH, M. N. (1990), Phys. Rev. Lett. **65**, 2390.

WALTZ, R. E., KERBEL, G. D., HAMMETT, G. W., and DOMINGUEZ, R. R. (1991), Bull. Am. Phys. Soc. **36**, 2278.

WALTZ, R. E. (1992), paper presented at the Transport Task Force meeting, Oak Ridge, Tennessee.

WARE, A. S., DIAMOND, P. H., CARRERAS, B. A., LEBOEUF, J.-N., and LEE, D. K. (1992a), Phys. Fluids B **4**, 102.

WARE, A. S., DIAMOND, P. H., BIGLARI, H., CARRERAS, B. A., LEBOEUF, J.-N., and CHARLTON, L. A. (1992b), Phys. Fluids B **4**, 877.

WEYNANTS, R., TAYLOR, R. J., VANDENPLAS, P. E., et al. (1990), in *Proceedings of the 17th EPS Conference on Controlled Fusion and Plasma Heating*, Vol. 14B, part I, 287.

WOOTTON, A. (1992a), "Edge Turbulence," in *Transport and Confinement in Toroidal Devices*, edited by C. Alejaldre and B. A. Carreras (Institute of Physics, Bristol, England), 47.

WOOTTON, A. (1992b), "Observations of Edge Turbulence in Tokamaks, Stellarators, and Reverse Field Pinches," paper presented at the 19th European Physical Society Meeting on Controlled Fusion and Plasma Physics, Innsbruck, Austria, June 29–July 3, 1992.

XU, X. Q., and ROSENBLUTH, M. N. (1992), Phys. Fluids B **3**, 1807.

ZARNSTORFF, M. C., BRETZ, N. L., EFTHIMION, P. C., et al. (1990), in *Proceedings of the 17th EPS Conference on Controlled Fusion and Plasma Heating* (European Physical Society) Vol. I, p. 39.

ZARNSTORFF, M. C., et al. (1991), in *Proceedings of the 13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research 1990* (IAEA, Vienna), Vol. 1, 109.

ZARNSTORFF, M. C. (1992), paper presented at the Transport Task Force meeting, Oak Ridge, Tennessee.

ORNL/TM-12209
Dist. Category UC-427

INTERNAL DISTRIBUTION

1. Director, ORNL Fusion Energy Division
2. C. C. Baker
3. L. A. Berry
4–13. B. A. Carreras
14. R. A. Dory
15. J. L. Dunlap
16. H. H. Haselton
17. M. S. Lubell
18. T. E. Shannon
19. R. P. Leinius
20–21. Laboratory Records Department
22. Laboratory Records, ORNL-RC
23. Central Research Library
24. Document Reference Section
25–26. Fusion Energy Division Library
27. ET/FE Division Publications Office
28. ORNL Patent Office
29. L. A. Charlton
30. C. L. Hedrick
31. S. P. Hirshman
32. J. T. Hogan
33. W. A. Houlberg
34. J.-N. Leboeuf
35. V. E. Lynch
36. M. Murakami
37. J. A. Rome
38. K. C. Shaing
39. K. L. Sidikman
40. D. A. Spong

EXTERNAL DISTRIBUTION

41. Office of the Assistant Manager for Energy Research and Development, U.S. Department of Energy Field Office, Oak Ridge, P.O. Box 2000, Oak Ridge, TN 37831
42. N. A. Davies, Director, Office of Fusion Energy, Office of Energy Research, ER-50 Germantown, U.S. Department of Energy, Washington, DC 20545
43. M. Roberts, International Programs, Office of Fusion Energy, Office of Energy Research, ER-52 Germantown, U.S. Department of Energy, Washington, DC 20545
44. D. E. Baldwin, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
45. R. W. Conn, Mechanical, Aerospace, and Nuclear Engineering Department, 6291 Boelter Hall, University of California, Los Angeles, CA 90024-1597
46. P. C. Liewer, MS 138-208, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109
47. D. Sigmar, Plasma Fusion Center, Massachusetts Institute of Technology, 167 Albany St., NW16-288, Cambridge, MA 02139
48. K. I. Thomassen, L-637, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
49. J. D. Callen, Department of Nuclear Engineering, University of Wisconsin, Madison, WI 53706-1687
50. S. O. Dean, Fusion Power Associates, Inc., 2 Professional Drive, Suite 248, Gaithersburg, MD 20879
51. H. K. Forsen, Bechtel Group, Inc., Research Engineering, P.O. Box 3965, San Francisco, CA 94119
52. R. W. Gould, Department of Applied Physics, California Institute of Technology, Pasadena, CA 91125

53. R. A. Gross, Plasma Research Laboratory, Columbia University, New York, NY 10027
54. R. J. Hawryluk, Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08543
55. D. M. Meade, Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08543
56. W. M. Stacey, School of Nuclear Engineering and Health Physics, Georgia Institute of Technology, Atlanta, GA 30332
57. D. Steiner, Nuclear Engineering Department, NES Building, Tibbetts Avenue, Rensselaer Polytechnic Institute, Troy, NY 12181
58. R. Varma, Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India
59. Bibliothek, Max-Planck Institut für Plasmaphysik, Boltzmannstrasse 2, D-8046 Garching, Federal Republic of Germany
60. Bibliothek, Institut für Plasmaphysik, KFA Jülich GmbH, Postfach 1913, D-5170 Jülich, Federal Republic of Germany
61. Bibliothek, KfK Karlsruhe GmbH, Postfach 3640, D-7500 Karlsruhe 1, Federal Republic of Germany
62. Bibliotheque, Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne, 21 Avenue des Bains, CH-1007 Lausanne, Switzerland
63. R. Aymar, CEN/Cadarache, Departement de Recherches sur la Fusion Contrôlée, F-13108 Saint-Paul-lez-Durance Cedex, France
64. Bibliothèque, CEN/Cadarache, F-13108 Saint-Paul-lez-Durance Cedex, France
65. Library, JET Joint Undertaking, Abingdon, Oxfordshire OX14 3EA, England
66. Library, FOM-Instituut voor Plasmafysica, Rijnhuizen, Edisonbaan 14, 3439 MN Nieuwegein, The Netherlands
67. Library, National Institute for Fusion Science, Chikusa-ku, Nagoya 464-01, Japan
68. Library, International Centre for Theoretical Physics, P.O. Box 586, I-34100 Trieste, Italy
69. Library, Centro Richerche Energia Frascati, C.P. 65, I-00044 Frascati (Roma), Italy
70. Library, Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Kyoto 611, Japan
71. Plasma Research Laboratory, Australian National University, P.O. Box 4, Canberra, A.C.T. 2601, Australia
72. Library, Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, 801-1 Mukoyama, Naka-machi, Naka-gun, Ibaraki-ken, Japan
73. G. A. Eliseev, I. V. Kurchatov Institute of Atomic Energy, P.O. Box 3402, 123182 Moscow, Russia
74. V. A. Glukhikh, Scientific-Research Institute of Electro-Physical Apparatus, 18863 St. Petersburg, Russia
75. I. Shpigel, Institute of General Physics, U.S.S.R. Academy of Sciences, Ulitsa Vavilova 38, Moscow, Russia
76. D. D. Ryutov, Institute of Nuclear Physics, Siberian Academy of Sciences, Sovetskaya St. 5, 630090 Novosibirsk, Russia
77. O. Pavlichenko, Kharkov Physical-Technical Institute, Academical St. 1, 310108 Kharkov, Ukraine
78. Deputy Director, Southwestern Institute of Physics, P.O. Box 15, Leshan, Sichuan, China (PRC)

79. Director, The Institute of Plasma Physics, P.O. Box 1126, Hefei, Anhui, China (PRC)
80. R. H. McKnight, Experimental Plasma Research Branch, Division of Development and Technology, Office of Fusion Energy, Office of Energy Research, ER-542 Germantown, U.S. Department of Energy, Washington, DC 20585
81. D. Crandall, Acting Director, Advanced Physics and Technology Division, Office of Fusion Energy, Office of Energy Research, ER-54 Germantown, U.S. Depart ment of Energy, Washington, DC 20585
82. E. Oktay, Division of Confinement Systems, Office of Fusion Energy, Office of Energy Research, ER-55 Germantown, U.S. Department of Energy, Washington, DC 20585
83. W. Sadowski, Fusion Theory Branch, Division of Applied Plasma Physics, Office of Fusion Energy, Office of Energy Research, ER-541 Germantown, U.S. Department of Energy, Washington, DC 20585
84. R. E. Mickens, Atlanta University, Department of Physics, Atlanta, GA 30314
85. M. N. Rosenbluth, University of California at San Diego, La Jolla, CA 92037
86. D. Schnack, SAIC, 10260 Campus Point Drive, San Diego, CA 92121
87. Duk-In Choi, Department of Physics, Korea Advanced Institute of Science and Technology, P.O. Box 150, Chong Ryang-Ri, Seoul, Korea
88. Library of Physics Department, University of Ioannina, Ioannina, Greece
89. C. De Palo, Library, Associazione EURATOM-ENEA sulla Fusione, CP 65, I-00044 Frascati (Roma), Italy
90. Laboratorio Associado de Plasma, Instituto Nacional de Pesquisas Espaciais, Caixa Postal 515, 122201, Sao Jose dos Campos, SP, Brazil
91. Theory Department Read File, c/o R. Hazeltine, University of Texas, Institute for Fusion Studies, Austin, TX 78712
92. Theory Department Read File, c/o D. J. Sigmar, Director, Plasma Fusion Center, NW 16-202, Massachusetts Institute of Technology, Cambridge, MA 02139
93. Theory Department Read File, c/o W. Tang, Plasma Physics Laboratory, Princeton University, P.O. Box 451, Princeton, NJ 08543
94. Theory Department Read File, c/o L. Kovrizhnykh, Lebedev Institute of Physics, Academy of Sciences, 53 Leninsky Prospect, 117924 Moscow, Russia
95. Theory Department Read File, c/o B. B. Kadomtsev, I. V. Kurchatov Institute of Atomic Energy, P.O. Box 3402, 123182 Moscow, Russia
96. Theory Department Read File, c/o T. Kamimura, National Institute for Fusion Studies, Nagoya 464, Japan
97. Theory Department Read File, c/o E. Maschke, Departemente de Recherches sur la Fusion Controlée, CEN/Cadarache, F-13108 Saint-Paul-lez Durance, France
98. Theory Department Read File, c/o D. Düchs, JET Joint Undertaking, Abingdon, Oxfordshire OX14 3EA, United Kingdom
99. Theory Department Read File, c/o R. Briscoe, Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, United Kingdom
100. Theory Department Read File, c/o D. Biskamp, Max-Planck-Institut fur Plasmaphysik, Boltzmannstrasse 2, D-8046 Garching, Federal Republic of Germany

101. Theory Department Read File, c/o T. Takeda, Japan Atomic Energy Research Institute, Tokai Fusion Research Establishment, Tokai-mura, Naka-gun, Ibaraki-ken, Japan
102. Theory Department Read File, c/o R. Waltz, General Atomics, P.O. Box 85608, San Diego, CA 92186
103. Theory Department Read File, c/o R. Cohen, Lawrence Livermore National Laboratory, P.O. Box 5511, Livermore, CA 94550
104. Theory Department Read File, c/o D. Burnes, CTR Division, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545

105–52. Given distribution according to OSTI-4500, Magnetic Fusion Energy (Category Distribution UC-427, Theoretical Plasma Physics)