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Transport Processes In Magnetically Confined Plasmas*

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ABSTRACT

Intensified studies of plasma transport in toroidal plasmas over the past three to five years have progressed through increased understanding in some areas and changed perceptions about the most important issues in other areas. Recent developments are reviewed for six selected topics: edge fluctuations and transport; L-H mode transition; core fluctuations; modern plasma turbulence theory; transient transport; and global scaling. Some of the developments that are highlighted include: the role of a strongly sheared poloidal flow in edge plasma turbulence, transport and the L-H transition; change of focus from $k_\perp \rho_s \sim 1$ to $k_\perp \rho_s << 1$ fluctuations in tokamak plasmas; modern Direct-Interaction-Approximation plasma turbulence and hybrid fluid/kinetic theoretical models; and transient transport experiments that are raising fundamental questions about our conceptions of local transport processes in tokamaks.

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I. Introduction

Developing an understanding of cross-field plasma transport is the "ultimate" scientific issue[1] for toroidal magnetic confinement systems (tokamaks, stellarators and reversed field pinches). Most other major plasma physics issues for toroidal systems are reasonably well characterized, understood and quantified: stable operating windows are determined by low q and high β ideal magnetohydrodynamic (MHD) linear stability limits; macroscopic phenomenology (sawteeth, Mirnov oscillations/locked modes, major disruptions, etc.) can be described reasonably well by nonlinear resistive MHD models; the Ohm's law parallel to the magnetic field is found experimentally to exhibit the predicted Spitzer, trapped-particle and bootstrap current effects; and plasma heating and current-drive can be quantified through the Coulomb collision effects on the neutral beam injection of and ion cyclotron range of frequency wave effects on fast ions, and the current responses to beam and wave momentum inputs. In contrast, cross-field plasma transport,[3] as a plasma physics subject, has been: not well characterized or understood in toroidal confinement systems; in need of realistic models of plasma turbulence and turbulent transport; and an outstanding physics conundrum of the late 20th century. Also, with respect to future experimental device designs, plasma transport has been: usually characterized by purely empirical energy confinement time (τ_E) scaling relations; and a key determinant of the plasma size and parameters needed for ignition.

The "standard" model of plasma turbulence, transport and confinement has many levels: 1) At the lowest level, "local" (small radial extent compared to the plasma radius, $\Delta x << a$) collective instabilities are driven by the local free energy associated with the plasma pressure, temperature and other gradients inherent in a confined plasma. The collective instabilities grow linearly from thermal noise in the plasma. They initially grow independently on the assumed nested equilibrium

magnetic flux surfaces. 2) The individual modes then saturate quasilinearly (at $\tilde{n}/n \sim k^{-1}\, d\, \ell n\, n/dr$ yielding $D \sim \gamma/k^2$), or, in the Direct-Interaction-Approximation (DIA), nonlinearly (at $\tilde{n}/n \sim \Delta_c\, d\, \ell n\, n/dr$ yielding $D \sim \Delta_c^2/\tau_c$). 3) Plasma turbulence with a fully developed spectrum of modes grows up and comes into an equilibrium, which is usually calculated via a DIA theory of the two-point correlation function. 4) The turbulent fluctuations in the plasma induce turbulent transport (with heat, particle diffusion coefficients χ, $D \sim (\Delta x)^2/\Delta t \sim \sum_k \Delta_{ck}^2/\tau_{ck}$) that acts to reduce the "local" ($\Delta x << a$) plasma pressure, temperature and other gradients. 5) The turbulent "radial" transport effects are incorporated into density, energy, etc. balance equations that are solved to yield the plasma density, temperature, etc. profiles in the plasma. 6) And, finally, the overall plasma confinement is determined by integrating these profiles over volume and dividing by their respective sources to determine the relevant confinement times [e.g., the energy confinement time $\tau_E \equiv 3/2 \int d^3x\, (n_e T_e + n_i T_i)/\int d^3x\, \Sigma Q \sim a^2/4\chi$]. The first four levels (linear growth, saturation, spectrum development and turbulent transport) must be developed self-consistently, even for "local" plasma turbulence and transport. Investigations in these first four areas are generally referred to as fluctuation studies. Those in the fifth level are called transport modeling while those in the last level are referred to as confinement studies.

The remainder of this brief review of our understanding of transport processes in magnetically confined plasmas is organized as follows. First, the reasons for increased emphasis on transport studies over the past three years are discussed. Thereafter, the contrasting characters of plasma edge and core turbulence and transport are discussed. Since space and time limitations do not permit a comprehensive review of all areas of plasma turbulence and transport, the following six sections highlight developments in six specific areas where there has

been notable recent (last three to five years) progress: edge fluctuations and transport; L-H mode transition; core fluctuations; modern plasma turbulence theory; transient transport; and global scaling. The areas of increased understanding and changed ideas about the important concepts are summarized in the final section.

II. Recent Status and Evolution Of Transport Studies

The transport status in the mid 1980s was characterized by success in empirical global confinement scaling but little understanding of the basic transport processes. Namely, the increase in τ_E by about an order of magnitude from the late 1970s and early 1980s experiments ($a \lesssim 50$ cm, plasma current $\lesssim 500$ kA) to the mid 1980s large-scale tokamaks (TFTR, JET, JT-60 with $a \gtrsim 1$ m, plasma current up to 5 MA) was predicted by empirical scaling relations developed from the smaller devices [e.g., the Goldston scaling[2] $\tau_E \sim I/P_{aux}^{1/2}$ for so-called L-mode confinement] to within a factor of about two. However, the "standard" physics-based model of plasma turbulence, transport and confinement outlined in the preceding paragraph did not seem to be borne out since it was not clear: if fluctuations were responsible for the local plasma transport; which theory (if any) of fluctuations and transport was applicable; why the theoretical models mostly predicted turbulent diffusion coefficients that decrease strongly from the center to the edge of the plasma while experimental data indicated gently rising coefficients; the tendency of the electron temperature profile to be approximately invariant ("profile consistency"[3]) was not theoretically predicted; the strong, nearly linear dependence of the energy confinement time on plasma current ($\tau_E \sim I$) did not seem to be predicted by the most prevalent drift-wave instability models with $k_\perp \rho_s \lesssim 1$, etc. Also, there were only very weak couplings between the experimental, modeling and theoretical studies of plasma turbulence and transport. Thus, there was the feeling that, while

the empirical scaling relations had worked quite well previously and might, with refinements, be sufficient for next generation devices and even perhaps reactors, the physical basis for plasma transport was not well understood. Also, there was the feeling that increased understanding should lead to enhanced, optimized plasma confinement in the future even larger scale and more expensive devices.

The desire for a more physics-based understanding of transport and more precise predictive confinement models in the late 1980s led to calls for increased emphasis on transport studies. Namely, during the winter of 1987 and spring of 1988 the Ignition Physics Study Group (led by J. Sheffield, ORNL), Compact Ignition Tokamak (physics part led by R.R. Parker, MIT) and International Tokamak Experimental Reactor (physics part led by D.E. Post, PPPL) future device design studies, and the Office of Fusion Energy (OFE) of the Department of Energy (DOE, initially W. Sadowski and later D.H. Crandall et al.) all highlighted the need for greater understanding of plasma transport. Also, the Coolfont Magnetic Fusion Advisory Committee (MFAC) Summer Study Panel called for[4] (as its second most important action initiative) a "National Confinement and Transport Task Force" to "improve predictive capability for tokamak confinement." In response, the author of this paper formed a Transport Task Force under the auspices of the Office of Fusion Energy of DOE in October of 1988. At about the same time, and essentially independently, the recently installed new director of the higher level Office of Energy Research in DOE decided that studies of transport should be the number one priority within the magnetic fusion program and began to redirect substantially program resources to reflect this prioritization. As a result of all these events, much greater emphasis was placed on studies of plasma turbulence and transport within the magnetic fusion program beginning from the fall of 1988.

The Transport Task Force (TTF), which was born amid the turmoil of major changes in direction of the magnetic fusion program during 1988-89, has fostered

and guided work on plasma turbulence and transport over the past three years. Its long-term goals are to:[5] Characterize local fluctuations and transport in toroidal plasmas, Understand the processes responsible for transport, and Identify how to Reduce transport in tokamaks -- that is, to CUIR transport in tokamaks. A key element in this endeavor has been to work toward a synthesis of theoretical, modeling and experimental studies of plasma turbulence and transport. The TTF has been guided by a 12 member Steering Committee comprised of fusion program leaders from most of the major programs in the U.S. During Phase I (October 1988 through March 1989) of the TTF, the status of transport studies were reviewed by seven Task Groups (comprised of about 70 members); summaries of their findings have been published.[6] During Phase II (April 1989 through the present) the TTF has promoted transport studies through bi-yearly workshops, for which some summaries have been written and published,[7] and formation of six working groups (beginning from March 1990) on edge fluctuations and transport, L-H transition, core fluctuations, grad-T_i modes (later changed to core transport), transient transport and dimensionless variable scaling. Additional groups have been formed recently as the author of this article resigned from the leadership of the TTF to go on sabbatical and B.A. Carreras of ORNL became the new leader of the TTF in May 1991.

III. Differing Characteristics of Edge and Core Plasma Turbulence and Transport

Because the properties of plasma turbulence and transport in the hot plasma core differ so much from those in the plasma edge (see Fig. 1), it is important to distinguish and discuss them separately. The edge fluctuations[6c,8] and local transport properties can be measured with metallic Langmuir probes inserted from outside the plasma. In the edge the fluctuations are found to be very large (of order the equibrium quantities), dominantly electrostatic and the cause of the local edge particle and heat transport.[8] The processes that generate plasma microinstabilities

in the edge plasma can be quite complex because the plasma is not fully ionized there and is thus susceptible to radiation cooling, ionization, charge-exchange and other atomic physics effects. These effects tend to reinforce the extant microinstabilities, generate new ones, and increase the fluctuation levels relative to those in the hot plasma core.[9]

In contrast, special diagnostics are required to measure the plasma fluctuations and transport in the hot (> 100 eV say) plasma core, which burns up metallic probes in a very short time (< 10 msec). Generally speaking, the fluctuations in the hot plasma core are small ($\lesssim 1\%$), and have significant electric and magnetic ($\tilde{B}/B \sim 10^{-4}$) components. At present, it is still not clear if the local fluctuations are responsible for the local transport in the hot core of the plasma. Since the edge and core regions are so different we discuss them separately in the following six sections -- the following two sections (edge fluctuations and transport, L-H mode transition) involve the edge, while the remaining four section sections are primarily concerned with core fluctuations and transport.

IV. Edge Fluctuations and Transport

Probe measurements in TEXT[8,9] over the past few years have clarified and expanded our previous knowledge[6c] about fluctuations and their effects on transport in the edge plasma. In particular, the edge fluctuations have been shown to be non-Boltzmann in character; that is, the density perturbations are not adiabatic with $\tilde{n}/n = e\phi/T_e$. Instead, as shown in Fig. 1, just inside the limiter at $r/a = 1$ one has $e\tilde{\phi}/T_e \sim 0.7 >> \tilde{n}/n \sim 0.25 >> \tilde{T}_e/T_e \sim 0.1$. Further, previous indictions[6c,10] that correlations between the edge density and potential fluctuations are responsible for the anomalous local particle flux in the edge have been reconfirmed and extended[6c,8] to show that correlations between the edge density, potential and electron temperature fluctuations are responsible for the anomalous edge electron

heat flux. Thus, apparently the plasma fluctuations in the plasma edge ($r/a \gtrsim 0.9$) do seem to be responsible for the anomalous transport fluxes there. [In contrast, similar comparisons in the core plasma region ($r/a \lesssim 0.9$) seem to show that the observed n, ϕ, and T_e fluctuations are not able to account for the observed core transport fluxes,[6c,8] largely because the fluctuations become so small in the core. However, if the dominant core fluctuations have large enough perpendicular wavenumbers ($k_\perp \rho_s > 0.3$) there is still some possibility[11] they may account for the observed transport fluxes.]

In attempting to develop theoretical models of edge plasma turbulence and transport it has been found that the electric field and its gradient play an important role in the plasma edge The equilibrium potential in toroidal plasmas[12] is usually negative (~ the ion temperature $\gtrsim$ 1 keV) in the plasma center, rises gently with radius to just inside the limiter where it rises quickly with radius to a small positive value ($\gtrsim$ 50 eV), and then decreases rapidly thereafter. The rapid variation of the potential at the edge leads to a large, negative electric field which however increases to a positive value just inside the limiter. This leads to a strong poloidal **E** x **B** flow which is also quite strongly sheared [i.e., $dV_\theta/dr \simeq - d(E_r/B)/dr$ is large]. That this could have a substantial effect on fluctuations in the vicinity of the limiter was recognized some time ago.[13] However, it has also been shown[14,15] that the position of this "shear layer" provides a good definition of the edge location for toroidal plasmas of all types (tokamaks, stellarators and reversed field pinches).

It has been found both experimentally[14,16] and theoretically[17-21] that large shear in the poloidal flow can tear apart turbulent eddies in the edge plasma and thereby reduce the plasma turbulence and turbulent transport they induce. The reduction in the radial decorrelation length of the turbulent eddies can be understood as follows. First, consider a model equation describing the evolution of

a density perturbation $\tilde{n}$ subject to shear in the poloidal flow in the x (or radial) direction and turbulent diffusion with coefficient D:

$$\frac{\partial \tilde{n}}{\partial t} + k_\theta x V_\theta' \tilde{n} - D \frac{\partial^2 \tilde{n}}{\partial x^2} = - \tilde{V}_x \frac{dn_o}{dr} . \tag{1}$$

The sheared flow and turbulent diffusion (last two terms on the left) are comparable within a radial "shear" layer of width

$$\Delta \sim \left(\frac{D}{k_y V_\theta'}\right)^{1/3}. \tag{2}$$

Since the scaling of D with $V_\theta' \equiv dV_\theta/dr$ is not yet determined, the scaling of the layer width with poloidal flow shear is also not clear. In the absence of shear in the poloidal flow ($V_\theta' = 0$), a single growing mode ($\partial\tilde{n}/\partial t = \gamma\tilde{n}$, with γ assumed to be independent of V_θ') has a mixing length saturation amplitude given by

$$\gamma\tilde{n} \sim \tilde{V}_x \frac{dn_o}{dr} \sim \frac{D_o}{\Delta_o^2} \tilde{n},$$

or

$$\tilde{n} \sim \Delta_o \, d n_o/dr, \; \tilde{V}_x \sim \gamma\Delta_o, \tag{3}$$

and hence

$$D_o \sim \gamma \Delta_o^2. \tag{4}$$

In the presence of strong shear in the poloidal flow ($k_\theta \Delta_o V_\theta' \equiv \omega_s >> \gamma$), using Eq. (2) one obtains within the shear layer

$$D \sim \gamma \Delta^2 \sim \gamma D_o^2 \left(\frac{\gamma}{\omega_s}\right)^2 << D_o \tag{5}$$

and hence

$$\Delta \sim \Delta_o \left(\frac{\gamma}{\omega_s}\right) << \Delta_o. \tag{6}$$

Thus, as shown in Fig. 2, a strong, externally imposed shear in the poloidal flow reduces the radial correlation length of the fluctuations, and hence their induced turbulent diffusion.

The real situation in the edge of toroidal plasmas is unfortunately usually more complicated, mainly because in a steady-state turbulent situation the "drive" is not a constant linear growth rate γ but rather is influenced by turbulent mixing, Reynolds stress flow generation and shear flow amplification effects due to radial propagation of the turbulence (a dynamo type effect). Then, the γ in Eqs. (3-6) above depends on V_θ' and the spectrum of the turbulence, and the entire problem must be solved self-consistently.[21] Experimentally there is evidence[14] that large poloidal flow shear reduces the radial decorrelation length, the decorrelation time, the fluctuation level, the local diffusion (since the density gradient increases there) and hence forms a sort of "transport barrier" in the edge shear layer.

Numerical models of plasma edge turbulence and transport have evolved considerably over the past few years. They began by considering rippling-mode turbulence,[22] plus radiation effects, and have gradually evolved to a model involving thermal-driven drift-wave instabilities with significant atomic physics (radiation, ionization, charge-exchange, etc.) and edge realism (large dV_θ/dr, limiter) effects.[20,21] The atomic physics effects tend to reinforce extant edge instabilities,

generate new ones, and create larger relative fluctuation levels in the edge than in the hot plasma core.[14] Nonetheless, the theoretically predicted fluctuation levels and radial decorrelation lengths often seem to be a factor of order three less than those experimentally observed. Work continues in this area with emphasis on getting and using more precise descriptions of the actual atomic physics effects in particular edge plasmas in order to make more quantitative and conclusive comparisons.

V. L-H Mode Transition

The normal mode of operation for auxiliary heated tokamak plasmas is called L-mode ("low mode") operation. It is characterized by energy confinement (τ_E^L) that degrades with increasing auxiliary heating power,[2] and by temperature and density profiles that go smoothly to very low values at the plasma edge ($T_e \lesssim 20$ eV, $n_e \lesssim 10^{19}$ m^{-3}). In contrast, the H-mode ("high mode") of operation[6c,23] (primarily in tokamak plasmas with divertors) is characterized by a factor of about two greater energy confinement ($\tau_E^H \lesssim 2\ \tau_E^L$) with a similar electron temperature profile but with a nearly flat density profile[24] that has a high boundary value ($n_e \sim 10^{20}$ m^{-3}). There is thus some indication that a "transport barrier" (at least for particle transport) exists at the plasma edge in H-mode plasmas. A key question is: what triggers the transition from L- to H-mode operation?

In concert with the developing picture of edge electric field effects, Shaing et al.[17,25] and Diamond et al.[18,19] have recently proposed and developed models for the L-H transition based upon these effects. The development of these models was stimulated and guided by careful edge studies[26] on the DIII-D tokamak of the properties of edge plasma flows, fluctuations and transport during the L-H mode transition. The comprehensive models that have emerged have six key elements: 1) A net radially outward ion current is induced in the edge layer plasma (due to ion

orbit losses,[17,25] asymmetric turbulence[19] near a divertor separatrix, or from an externally inserted biased probe). 2) This radial current leads to a $\mathbf{J}_r \times \mathbf{B}$ force on the plasma that is damped by the neoclassical viscous force[27,28] on poloidal flows. 3) If the induced poloidal force is large enough it can overcome the viscous damping and induce a large (but usually still slightly subsonic) poloidal flow, and shear in the poloidal flow in the edge layer. 4) For sufficiently strong poloidal flow shear, turbulent eddies get torn apart by the electric field effects discussed in the preceding section. 5) The shearing effect reduces the fluctuation level. 6) And, the reduced fluctuation level reduces the anomalous transport in this edge layer and thus produces a "transport" barrier. In the Shaing et al. model[17,25] these are effectively sequential steps that can be calculated somewhat independently because the initiating radial ion current is externally imposed. In contrast, in the Diamond et al. model[19] since the initial radial ion current is induced by asymmetries in the turbulence (about a given mode-rational surface), all of the elements must be calculated self-consistently taking cognizance of the turbulence effects at each stage. Both models can produce bifurcated solutions indicative of the L- and H-mode operating regimes.

The basic elements of this L-H transition model have been developed and confirmed by DIII-D data,[29] as shown in Figure 3. Namely, at the L-H transition the edge poloidal flow rotation jumps (in a narrow layer a few cm in width), while fluctuations and the particle flux out of the plasma (indicated by the D_α signal) drop substantially. Perhaps the most critical test of any model is to use it to develop methods for reducing transport -- the Identify how to Reduce part of CUIRing transport. This critical test was provided[30] by negatively biasing a probe inserted into the plasma in the CCT tokamak. The result, as shown in Fig. 4, was that after a short period the plasma changed from L- to H-mode operation, as would be predicted by the six element model described in the preceding paragraph. In

addition, a positive bias experiment[31] in the TEXTOR tokamak also succeeded in inducing an L- to H-mode transition. Also, the poloidal flow-retarding force has been shown[32] to agree with neoclassical viscous force predictions. Further ancilliary developments related to the L-H transition include determination[33] of the interrelationships between the poloidal (and toroidal) flows for various plasma impurities (since it is the impurity not hydrogenic flows that are measured spectroscopically), and localized transient transport modeling[34] of the L-H transition and of the edge plasma after an Edge Localized Mode[35] (ELM) "crash." The general perspective that emerges from all these experimental results, tests and modeling thereof is that while there is still considerable disagreement on the details of each of the six basic elements of the L-H transition model and certainly their causal interrelationships, this comprehensive model explains many key features of the L-H transition and provides a very useful framework for describing it.

VI. Core Fluctuations

While low level ($\lesssim 1\%$) core density fluctuations have been measured by microwave scattering for some time,[6c,36] a new generation of scattering diagnostics on the TEXT, TFTR and ASDEX experiments in the late 1980s has helped clarify some key aspects of these fluctuations. These new diagnostics have better spatial resolution (small scattering volume, $\Delta X_{det} \lesssim a/3$) and can measure smaller wavenumbers ($k_\perp \rho_s < 1$, where $\rho_s \equiv c_s/\rho_i$ is the ion gyroradius measured at the ion sound speed) than previously. What has been found,[37] as shown in Fig. 5, is that the smallest measurable wavenumbers ($k_\theta \rho_s \lesssim 0.4$) have the largest fluctuation levels, and that these smallest wavenumber fluctuations increase most strongly as auxiliary heating power is applied (and $\tau_E{}^L$ degrades). Also, it has been found[38] that the frequency spectrum ($\gtrsim 100$ kHz) observed in the laboratory frame is almost entirely determined by the shear-flow-induced (see section IV) Doppler frequency

spread ($\Delta\omega \simeq k_\theta \, \Delta X_{det} \, dV_\theta/dr$). After subtracting out this effect, the net frequency spread in the moving plasma rest frame often is obscured by the net diagnostic resolution ("ghost" features) and must be less than about 50 kHz. Since the largest fluctuations occur at the lowest wavenumbers measurable and are proportional to k_θ and the width of the detection volume, the complicating sheared flow Doppler shift effects found in this new generation of diagnostics indicated that in order to make further progress smaller **k** (namely, $k_\perp < 2$ cm^{-1}) fluctuations needed to be measured with much finer spatial resolution.

Thus, in the late 1980s three new types of fluctuation diagnostics were developed with small detection volumes ($\Delta X_{det} \sim 1$ to 2 cm) to measure the $k_\perp \rho_s \ll 1$, $k_\perp < 2$ cm^{-1} part of the fluctuation spectrum: Heavy Ion Beam Probe[39] (HIBP) on TEXT, Beam Emission Spectroscopy (BES)[40,41] on PBX-M, Phaedrus-T and TFTR since 1989, and Correlation Reflectometry (CR)[42,43] on JET and TFTR since 1990. The common features found from all these diagnostics are that the largest fluctuations ($\tilde{n}/n \sim 1\%$) have $k_\theta \rho_s \lesssim 0.1$ and radial correlation lengths that range up to 2 to 3 cm (largest in the poorest confinement regimes). The perpendicular scale lengths of the fluctuations can thus be at least of order 10 ρ_s ($\rho_s \lesssim 0.2$ cm), or a few ion banana drift orbit widths ($\Delta r_T \sim 1$ cm). In fact, the BES measurements[41] in TFTR L-mode plasmas indicate a radial correlation length of about 25 ρ_s, density fluctuation levels about a factor of 4 larger than the mixing length estimate [see Eq. (3)], and that the absolute fluctuation level for $k_\perp < 2$ cm^{-1} is apparently roughly as would be implied by the extrapolation of the upper curve in Fig. 5 into this low k_θ region. Also, the fluctuation levels in the plasma core (but not the edge) seem to be correlated with the global energy confinement time τ_E -- BES measurements[44] on TFTR show that $\tau_E \sim \tilde{n}^{-1}$ while CR measurements[42] on JET show that the radial correlation lengths of the fluctuations are longest in L-mode plasmas and smaller in H-mode and ohmic plasmas. The radial and poloidal arrays of BES detectors on

TFTR yield additional information. Namely,[41] the cross-phase frequency spectra between different poloidal detectors show that the already narrow frequency spectrum (~ 30 kHz) is again dominated by Doppler shifts due to plasma flow effects. The net frequency spread in the plasma rest frame after these effects are subtracted out is below the experimental uncertainty of perhaps 5 kHz. (For the relevant tokamak discharges a drift wave with a poloidal mode number m = 30 would have a diamagnetic flow frequency of about 5 kHz). It should also be mentioned that Thomson scattering systems on JET and TFTR have seen hints[44,45] of "flat-spots" on the measured electron temperature profile with widths up to about 10 cm, which would imply a radial correlation length of about 5 cm. However, it is difficult to determine if such structures are really present since the photon statistics yield large diagnostic uncertainties for such fine scale phenomena.

The picture that is emerging from these new diagnostics is thus that the largest fluctuations in the hot core of tokamak plasmas have $k_\perp \rho_s \lesssim 0.1$, long radial correlation lengths $\gtrsim 10\ \rho_s$, and very low frequencies in the plasma rest frame (less than perhaps 5 kHz, comparable to the ion collision frequency ν_i). Using a mixing-length-type estimate for the diffusion coefficient [cf., Eq. (4)] with a radial decorrelation length for the turbulent fluctuations of 2 to 3 cm, a decorrelation time of order 0.1 - 1 msec would be sufficient to yield the experimentally observed anomalous diffusion coefficients (see Section VIII) of about 10^4 cm^2/sec. Thus, the largest fluctuations do not seem to be described by the $k_\perp \rho_s \gtrsim 0.5$ "collisionless" drift wave ($\omega \sim \omega_{*e} >> \nu_i$) models that have usually been invoked to explain the plasma core fluctuations and transport.[46,47] Rather, they are of such low frequency and long wavelengths that they should be describable primarily with fluidlike models, as will be discussed in greater detail in the next section.

VII. Modern Plasma Turbulence Theory

Major advancements in theoretical studies of plasma turbulence and transport over the past 5 years can be split into five categories: DIA-type models, numerical calculations of drift-wave type turbulence, hybrid fluid/kinetic descriptions, magnetic structure type models, and the beginning evolution to models that emphasize small $k_\perp\rho$. The following paragraphs give brief summaries of recent developments in these respective areas.

Direct-Interaction-Approximation (DIA) models of statistical plasma turbulence have been very aggressively developed over the past 5 years.[21] In a crude manner of speaking, what the simplest of these models do is to use renormalization techniques to determine the form of the turbulent diffusion coefficient D in Eq. (1) in terms of sums (or integrals) over the turbulence spectrum. In contrast to fluid turbulence where there is only one key turbulent field (the vorticity $\omega = \nabla \times \mathbf{V}$), in plasma turbulence one needs to treat simultaneously[48-50] a number of active and passive scalar fields (e.g., vorticity $\nabla^2\tilde{\phi}$, density $\tilde{n}$, magnetic flux $\tilde{\psi}$, parallel flow $\tilde{V}_{\parallel i}$, parallel current $\tilde{J}_\parallel$ and other fluctuating quantities). Also, both fluidlike and adiabatic[49] nonlinear responses must be handled simultaneously[50] for both the electron and ion species in a plasma. Further, a DIA-theory of the two-point correlation function has been developed to determine the fluctuation spectrum. That these DIA-models are relevant for describing plasma turbulence has been shown through comparison with numerical calculations of resistive-g mode turbulence.[52] There, it was shown that while mixing length models such as in Eqs. (3, 4) can give the dominant scaling of D with plasma parameters for fluidlike turbulence, the DIA theory determines the coefficients -- by balancing the fluctuation drives against the turbulent diffusion effects. Recently, the anomalous transport induced by trapped-particle instabilities[53] has been reinvestigated using these DIA procedures and it has been found that the induced transport is much smaller than usually estimated, with the trapped-ion transport coming down to the

previously estimated trapped-electron level.[54] Finally, the DIA theories have played an important role in the investigation of the velocity shear effects[17-22] on edge plasma turbulence and transport that was discussed in Section III above.

Since estimates of the transport that ion-temperature-gradient (ITG)-driven modes could induce[48] were so large and there were some indications that, at least in equilibrium situations,[55] these modes might play an important role in L-mode transport, a number of numerical calculations[56] of the turbulence and transport that these modes induce were developed over the past few years. While the first calculations tended to confirm that these modes could cause substantial transport, as more and more realistic effects (particularly kinetic ones) have been incorporated into the calculations the net level of induced transport has gotten progressively smaller. At present the general conclusion seems to be that the ITG modes are not likely to produce enough anomalous transport to account for the experimentally observed levels ($D, \chi_i \gtrsim 10^4$ cm^2/sec) in tokamak plasmas, particularly over the outer half of the plasma; however, in the hotter inner half of the plasma they may induce enough transport to contribute significantly to anomalous transport there.

A major difficulty that arises in developing numerical calculations of plasma turbulence is that truly realistic models of it would require computer resources well beyond the largest and most powerful supercomputers presently available. Thus, reduced phase-space models must be used and even then the calculations are at the "grand challenge" level[57] of computations. One of the key problems in developing such models is that, apparently, some kinetic effects need to be included in the computational models -- to take into account physically important effects (e.g., due to trapped-particles, Landau damping and perhaps finite gyroradius), and to dissipatively limit the mode-coupling effects which tend, in high temperature plasma simulations, to couple all modes together, and to the plasma boundaries. Thus, recently, methods have been developed[58-61] to include Landau damping and

other kinetic effects in fluidlike models that involve only the lowest order fluid moment equations (e.g., density, flow velocity, temperature), with closure moments for the fluid moment hierarchy being determined kinetically. The pioneering procedures [58,59] developed for doing this, while relatively successful for ITG-mode applications, were somewhat ad hoc. A rigorous Chapman-Enskog-like procedure[50,61] has now been developed to derive a rigorously valid equation for the non-fluid kinetic distortion of the distribution function away from a "dynamic" Maxwellian and to determine the needed semi-kinetic closure moments for the fluid equations. This new procedure has also been used to derive[61] extensions and more exact forms of closure relations that have been used previously.[48,58,59] This work is also making possible a whole new generation of fluidlike descriptions of tokamak plasmas including all the important neoclassical,[60] kinetic[61] and semi-collisional[61] effects.

As discussed in Section II, in "standard" theoretical models of plasma turbulence and transport one begins by assuming that the magnetic flux surface topology consists of nested, well-defined surfaces. Recently, investigations have begun into models where the "equilibrium" has a (perhaps time-varying) mix of good flux surfaces, magnetic islands and stochastic magnetic field regions. The radial scale sizes (the island widths) in these models range from very small[62] (0.1 cm $\sim c/\omega_{pe} \lesssim \Delta x_\perp \lesssim \rho_s \sim 0.2$ cm), through slightly larger than the ion gyroradius ($\Delta x_\perp \gtrsim \rho_s \sim 0.2$ cm) self-sustained situations,[63] to a more fluidlike "magnetic bubbling" of bootstrap-current-driven interacting mini-magnetic islands[64] ($\Delta x_\perp \sim$ few cm). Also, a statistical mechanics of interacting current filaments which leads to a "natural" current profile has been set forth.[65] While these models are still embryonic, they provide an important new paradigm for theories of plasma turbulence and transport in tokamaks.

As the experimental data on core fluctuations has improved over the past few years (see preceding section), it has become increasingly clear that whereas most previous theoretical work on plasma turbulence and transport has concentrated on $k_\perp \rho_s \gtrsim 0.5$ drift-wave type instabilities and turbulence, much longer perpendicular wavelength modes ($k_\perp \rho_s < 0.1$) have the largest fluctuation levels and need to be considered in much greater detail. The only obvious candidate instabilities in this long wavelength range are the trapped-ion modes,[53,54] which can produce primarily electrostatic convective cells mostly localized between mode-rational surfaces, and the neoclassical MHD tearing-type modes[28,66] which can produce destructively-interacting mini-magnetic islands[64] centered on mode-rational surfaces. Alternatively, one could have an inverse cascade in k-space (due to the nonlinear polarization drift[67]) feed the small $k_\perp \rho_s$ region. However, below $k_\perp \rho_s \sim 0.3$ the $\mathbf{E} \times \mathbf{B}$ convection nonlinearity becomes dominant[68] and it produces a regular (i.e., neutral-fluid-type) cascade to larger k. Clearly there needs to be much more theoretical work on possible low $k_\perp \rho_s$ (< 0.1) instabilities and/or nonlinear excitations, and the plasma turbulence and transport they induce.

VIII. Transient Transport

The transport responses due to localized transients in toroidal plasmas (e.g., due to sawtooth crashes, modulated electron cyclotron heating, oscillating gas puff, pellet injection) are usually found to be governed by diffusive processes.[6d,69-73] However, the diffusivity coefficients ($\sim 3 \times 10^4$ cm^2/sec) so determined are usually somewhat larger (by factors of about 2 to 5 or more) than their inferred equilibrium values ($\sim 10^4$ cm^2/sec). Any comprehensive model of plasma transport transient responses should be able to explain both the equilibrium and transient responses (if they are not so rapid or local as to be on the scale of the fluctuations causing the transport). In this regard, incremental heat transport properties, nonlinear heat

flux, and heat pinch models have been invoked to try to relate the two, although no one model seems totally successful.

Various types of electron (or total) heat diffusion coefficients have been deduced from: the equilibrium power balance[74] (χ_e^{PB}) as the ratio of local heat flux to $-n\nabla T$; heat pulse propagation transients (χ_e^{HP}) induced by sawtooth crashes;[69-71] changes in $-n\nabla T$ with changes in heat flux[71,75,76] (χ^{flux}); the global incremental energy confinement time[75] for additional auxiliary heating ($\chi^{inc} \sim a^2/4\tau_{inc}$); modulated electron cyclotron heat wave responses[77] (χ_e^{HW}); etc. All these methods of determining the heat diffusion coefficients seem to give slightly different results, although sometimes many of the transiently determined ones agree to within the experimental uncertainties.[71,72,75] Diffusivities for transport processes other than for electron and total heat have also been determined -- fast ions[78] ($D_{fast} \lesssim 10^3$ cm^2/sec), runaway electrons[79,80] ($D_{run} \sim \chi_e^{PB}$, but can be larger[79] or smaller[80]), impurities ($D_{imp} \sim D_{ions}$), toroidal momentum ($\chi_\phi \sim \chi_i^{PB} \sim \chi_e^{PB}$), etc. While there is a tendency for the transient electron heat diffusivities to be the largest ($\chi_e/D \sim 10$ in JET[72,81]), and the fast ion and particle diffusivity (D) to be the smallest, most of the other diffusivities are comparable and have intermediate values.

Recently, there has been some controversy and further developments concerning the use of sawtooth crashes for investigating electron heat transport. Namely, Fredrickson et al.[82] have shown that there is an approximately 200 μsec "ballistic" response that extends significantly beyond the usual sawtooth mixing radius and that this can complicate the subsequent transport analysis. In a different vein, Sips et al.[81,83] have shown that on JET the inclusion of coupled density as well as electron temperature responses greatly improves the experimental fits to the transient responses. The same authors also show how their model can be used to reconcile[83] the seemingly different results on JET[81] ($\chi_e/D \sim 10 >> 1$) and TEXT[84]

($\chi_e/D \sim 1$) -- through the degree of initial excitation of the coupled density, temperature eigenmodes.

Transport processes for the plasma density have also been explored -- through oscillating gas puff experiments. Here, a nonlinear particle flux form [$\Gamma \sim -T_e^2 (\nabla n)^3/n^2$] was deduced[73] from such experiments with small perturbations on TFTR. Perhaps more remarkable is the fact that use of this particle flux in transport modeling of density profile responses to injection of a sequence of large pellets was quite successful. Thus, a nonlinear model derived from "small" perturbations was successful in modeling "large" transient responses.

Most of the preceding discussion of transient transport has involved perturbing the plasma in various random ways and analyzing the resultant transport responses to see what one can learn. In particular, the experiments have mostly not been structured to probe particular plasma turbulence and transport models. Recently, a new class of experiments especially designed to test particular theoretical models have come into being.

In one of the first such experiments designed to test a particular theory, Zarnstorff et al.[86] attempted to explore the role of ion-temperature-gradient (ITG) modes (see Section VII) in L-mode tokamak plasmas. The particular theoretical attribute to be tested was the fact that these modes were predicted to dramatically increase the ion heat transport when the ion temperature gradient parameter [$\eta_i \equiv d\,\ell n\, T_i/dr) / (d\,\ell n\, n_i/dr)$] exceeds a critical value.[48] In the experiment a pellet was injected causing the ion density gradient to nearly vanish near where the pellet stops in the plasma. This causes the parameter η_i to rapidly increase from an initially nearly critical value ($\eta_i \sim \eta_{i_{crit}} \sim 2$) to a much larger value ($\eta_i \gtrsim 10 >> \eta_{i_{crit}}$). While the simplest theory predicts that the ion heat transport should have increased dramatically, the ion temperature profile and ion heat transport were nearly unchanged. Thus, the theoretically-predicted ITG mode was apparently not

operative in these TFTR discharges. Subsequent numerical calculations[56] of ITG mode turbulence and transport have concluded that these modes do not increase the ion heat transport so dramatically for $\eta_i \geq \eta_{ic}$, and that the maximum transport is not so large. The net conclusion seems to be that the ITG modes are not a significant transport factor, at least in TFTR discharges.[86]

Another new type of experiment[87,88] was designed to test the strong current scaling in the global energy confinement[2] ($\tau_E \sim I$). Namely, in TFTR the plasma current was ramped down (or up) in a time (~ 0.3 sec) long compared to the energy confinement time (~ 0.05 sec) but short compared to the magnetic skin diffusion time to the $q \sim 1$ surface (~ 3 sec). It was thought that this experiment would test the supposition that anomalous transport depends strongly on the poloidal magnetic field in the outer regions of the plasma, such as would be predicted by various resistive[89] and neoclassical[90] MHD pressure-gradient-driven turbulence models. What was found experimentally[87,88] on TFTR was that the energy confinement time τ_E did not change significantly with the plasma current I, even though the poloidal magnetic field and magnetic shear in the outer region did change predictably. Rather, τ_E apparently did not change until the internal inductance changed on the magnetic diffusion time scale. Similar experiments on ASDEX, JET and DIII-D have confirmed these results and shown that they are generic. There is some possibility[91] that a local transport model, which depends on just the right combination of poloidal field and magnetic shear to not change during the current-ramp but still has the poloidal magnetic field dependence in equilibrium needed for global confinement scaling, can be made to work. However, these quite remarkable current-ramp results seem to imply that net, "equilibrium" transport is determined by the current profile and its slow magnetic skin diffusion time scale -- global control of local transport via the slowly evolving current profile?

Another class of transient transport experiments that is producing results which are challenging our basic concepts of locally determined anomalous transport are obtained with electron cyclotron heating (ECH). As shown in Figure 6, strong off-axis ECH in DIII-D produces[92,93] a more highly peaked electron temperature profile than would be predicted from a local electron heat transport model. (The authors state specifically[92] that the "peaked temperature profile in Fig. 6 cannot be explained by 'profile consistency'[3] since the shape of the electron temperature profile varies with the ECH deposition location.") The fact that the electron temperature peaks so much inside the ECH heating radius implies a non-diffusive inward flow of electron heat (but the total ion plus electron heat flow is still outward) -- due to an electron "heat pinch" or an unusual nonlocal response? Another presently incomprehensible result from ECH has been produced in TEXT where[94] the fluctuation level at the center of the plasma becomes largest not when the ECH heating is localized there, but rather when it is placed at about the half-radius of the plasma. Again, ECH seems to induce a nonlocal response. Finally, large temperature fluctuations have been induced[95] in the Dutch tokamak RTP by highly localized ECH at the plasma center. The authors of this work suggest the large fluctuations may be the result of filamentary[65] or magnetic island type[62-64] magnetic structures like those discussed at the end of Section VII. In summary, while there are still some questions concerning whether the ECH power is all getting deposited in the predicted (and sometimes verified experimentally, in the initial phase) regions, it seems that highly localized ECH may be inducing inexplicable nonlocal and/or nonlinear responses.

While definitive conclusions cannot yet be drawn from these transient transport experiments, they do seem to be challenging the basic notions of locally determined turbulence and turbulent transport in the "standard model" discussed in Section II. Namely, while transport responses to localized transients do seem to

be diffusive, they seem to be rapid compared to the net, equilibrium transport, which may be governed by the very slowly evolving current profile. Also, there are some indications from the current-ramp and off-axis ECH experiments that some presently incomprehensible nonlocal effects may be operative -- globally determined local fluctuations and diffusive transport?

IX. Global Scaling

There have also been some developments in global scaling and other general properties of tokamak plasma confinement over the past 3 to 5 years. Namely, the question[75] of power law ($\tau_E \sim P^{-1/2}$) versus offset-linear scaling ($W \sim W_o + \tau_{inc} P$) has evolved from a discussion involving global parameters (where the experimental uncertainties prevent concluding which is more appropriate) to the local level (where, as discussed in the preceding section, it seems the plasma has both linear and nonlinear transport flux responses). Also, many factors (fast ion components, edge pedestal boundary conditions, sawteeth, ELMs, $\chi(r)$ profile, etc.) have been shown[2,75] to contribute to τ_E (or τ_{inc}) and hence to cloud the global confinement scaling issue.

Further, it has been found that rigid "profile consistency"[3] does not adequately characterize the T_e profiles in tokamaks -- because T_e does change slightly in response to changes in the heating profile, and often does so roughly as predicted[75] given that the temperature profile results from a double integral of the heating profile. However, since the T_e profile does seem to be fairly hard to change, it has been suggested[96] that "profile resiliency" would be a more appropriate descriptor of the situation. A "profile data base" being assembled[97] at the University of Texas under DOE sponsorship may be helpful in exploring the degree and veracity of this new characterization of the T_e profile responsiveness.

With regard to global scaling relations, the ITER program has developed some comprehensive new L-mode scalings.[98] Also, an ITER H-mode data base[99] comprised of experimental results from the ASDEX, DIII-D, JET and JFT-2M tokamaks has been assembled. In interpreting the scaling relations obtained from these data bases, plasma-physics-based dimensionless-variable[100] forms have been developed in addition to the usual "engineering variable" forms. The data are found to fit the dimensionless-variable-forms with about the same variance as the engineering variable forms. In addition, it has been shown[102] that the inferred scaling relations are consistent with the governing equations of plasma physics. Finally, scaling experiments in which one attempts to hold all but one of the key dimensionless variables (e g., β, collisionality or ratio of gyroradius to plasma radius) constant have been undertaken.[103] Changing heating profile effects complicate these scaling studies. Also, there are still some disagreements about the various results among the groups working in this area. Nonetheless, the concensus seems to be that the results favor a Bohm-like (implying large-scale structures) rather than gyro-Bohm-like (implying small-scale structures tied to the ion gyroradius) scaling. However, new types of experiments now being undertaken can be expected to add to our knowledge in this area.

X. Summary

People often ask if we understand transport yet. This brief review of developments over the past 3 to 5 years should make clear that while we are approaching some understanding of plasma turbulence and transport in the edge, we surely do not yet understand it in the core plasma. However, one should really ask if we made any progress in CUIRing transport. Here the answer is surely yes since our understanding has increased in some areas and in other areas new issues

have emerged while some old issues have been resolved. Specific progress of this type in the various areas reviewed here has been as follows:

1) Edge fluctuations and transport. It is now even clearer than before that electrostatic fluctuations cause the particle and heat transport in the edge plasma. Shear in the poloidal velocity has been found to play a very important role in the edge fluctuations, turbulence and turbulent transport.
2) L-H mode transition. A comprehensive model based on the radial electric field or poloidal flow velocity shear effects has begun to take shape.
3) Core fluctuations. The frequency spread due to the inhomogeneous Doppler shift in the sheared flows has been shown to dominate the observed frequency spectrum. A new generation of diagnostics has shown that the largest fluctuations have $k_\perp \rho_s \lesssim 0.1$ and thus shifted attention to long-scale-length (compared to the gyroradius) collective structures.
4) Modern plasma turbulence theory. DIA-based theories that take into account multiple scalar fields, fluid and adiabatic species, and trapped-particle effects have been developed. Hybrid fluid/kinetic models which include important kinetic effects in fluidlike equations have become a reality. Studies of small $k_\perp \rho_s$ ($\lesssim 0.1$) instabilities and turbulence are beginning to be emphasized.
5) Transient transport. Transport responses to localized transients still seem diffusive. However, current-ramp, off-axis ECH and other experiments indicate that the net, equilibrium transport fluxes may have nonlinear functionals and be determined by nonlocal processes, perhaps on the slow current profile evolution time-scale. If borne out, these effects bring into question the entire standard model (see Section II) of plasma turbulence and transport based upon local processes. Also, if the plasma response is nonlinear and nonlocal, how should we analyze experimental data to determine the relevant characterizations of plasma transport?

6) Global scaling. This has worked well in predicting the plasma confinement properties of the present large-scale tokamaks (JET, JT-60 and TFTR). Also, the scaling relations are being improved through the removal of extraneous (non-transport) effects, casting of them in dimensionless variable forms, etc. However, we still seem far short of being able to deduce them from a physics-based local (or nonlocal?) model.

Thus, while transport is certainly not yet a solved issue, considerable progress has been made in CUIRing transport over the past 3 to 5 years. At present, a number of diagnostic, experimental, modeling and theoretical studies that have been initiated only recently are beginning to come to fruition. Hence, continued strong emphasis on transport studies is needed for at least a few more years to obtain results from these programs and thereby move substantially closer to the goal of CUIRing transport.

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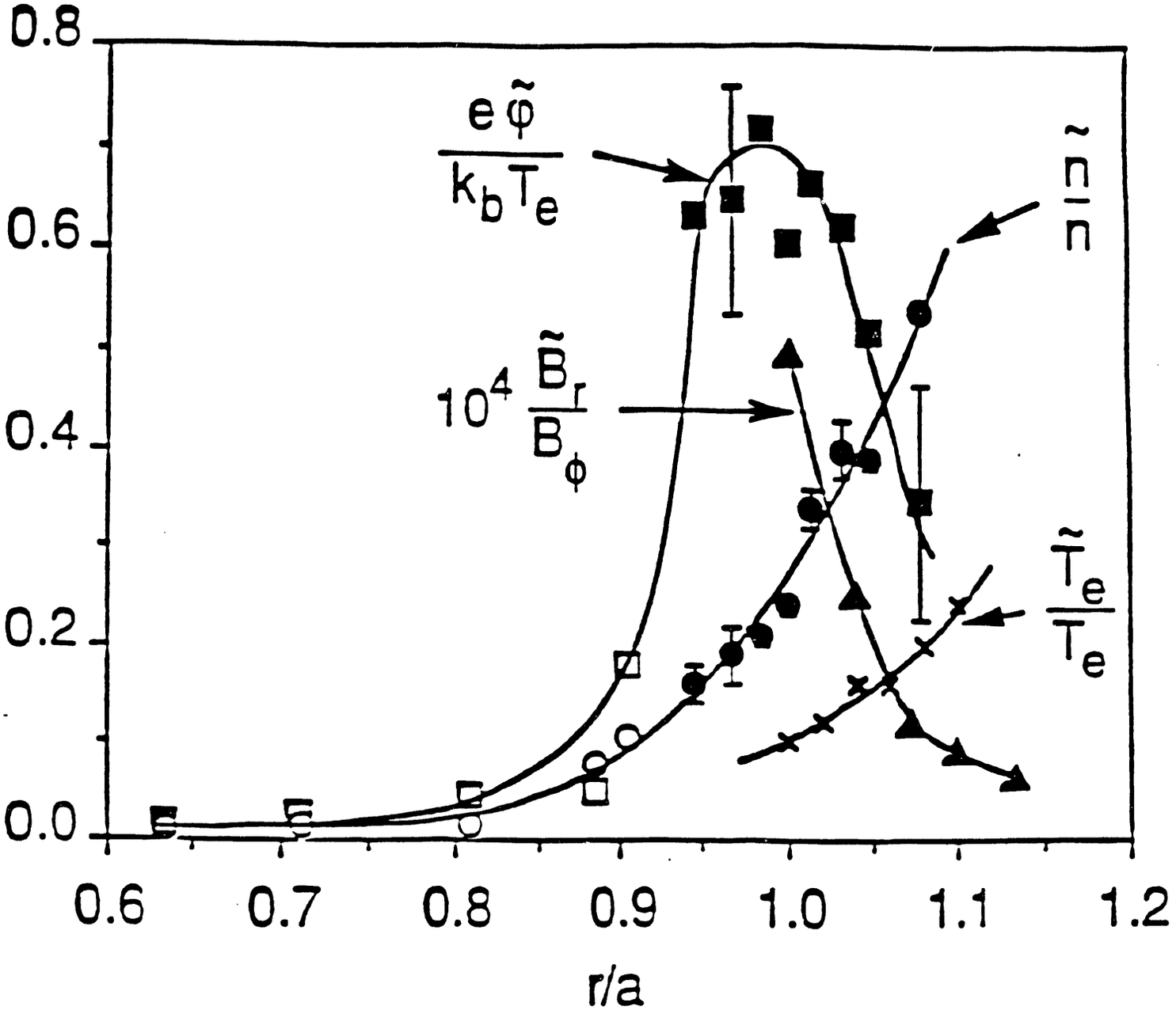

Figure 1. The electrostatic fluctuation level measured by externally inserted Langmuir probes in the plasma edge ($r/a \gtrsim 0.9$) of the TEXT tokamak is large (up to 70%). The fluctuation level drops sharply going inwards past the limiter ($r/a \simeq 1$) and the region of strong poloidal flow shear ($r/a \simeq 0.95$). In the hot core ($r/a \lesssim 0.8$) of the plasma the potential and density fluctuations are small ($\lesssim 1\%$). In contrast, the magnetic fluctuation level is very small at the plasma edge but apparently rises to a significant level ($\tilde{B}_r/B \gtrsim 10^{-4}$) in the hot core plasma (from refs. 6c, 8).

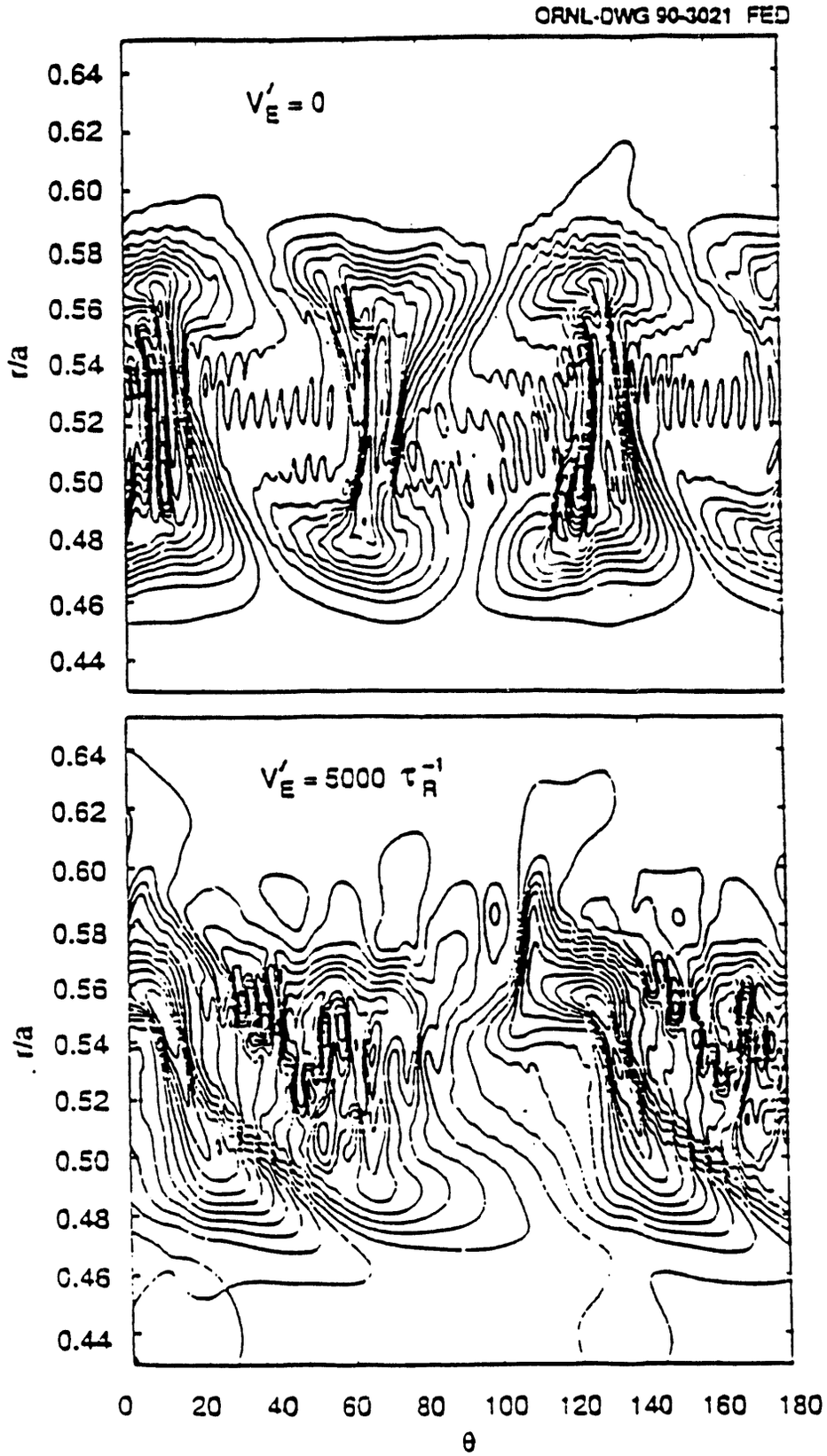

Figure 2. Numerically calculated changes in edge plasma turbulence characteristics caused by a sheared poloidal flow $V_\theta' = dV_\theta/dr$. The lines show contours along which the density fluctuations $\tilde{n}$ are constant. The poloidal (θ) flow shear has a shearing effect on the turbulent structures, which reduces the basic radial correlation length of the turbulence and the plasma transport it induces (from ref. 19).

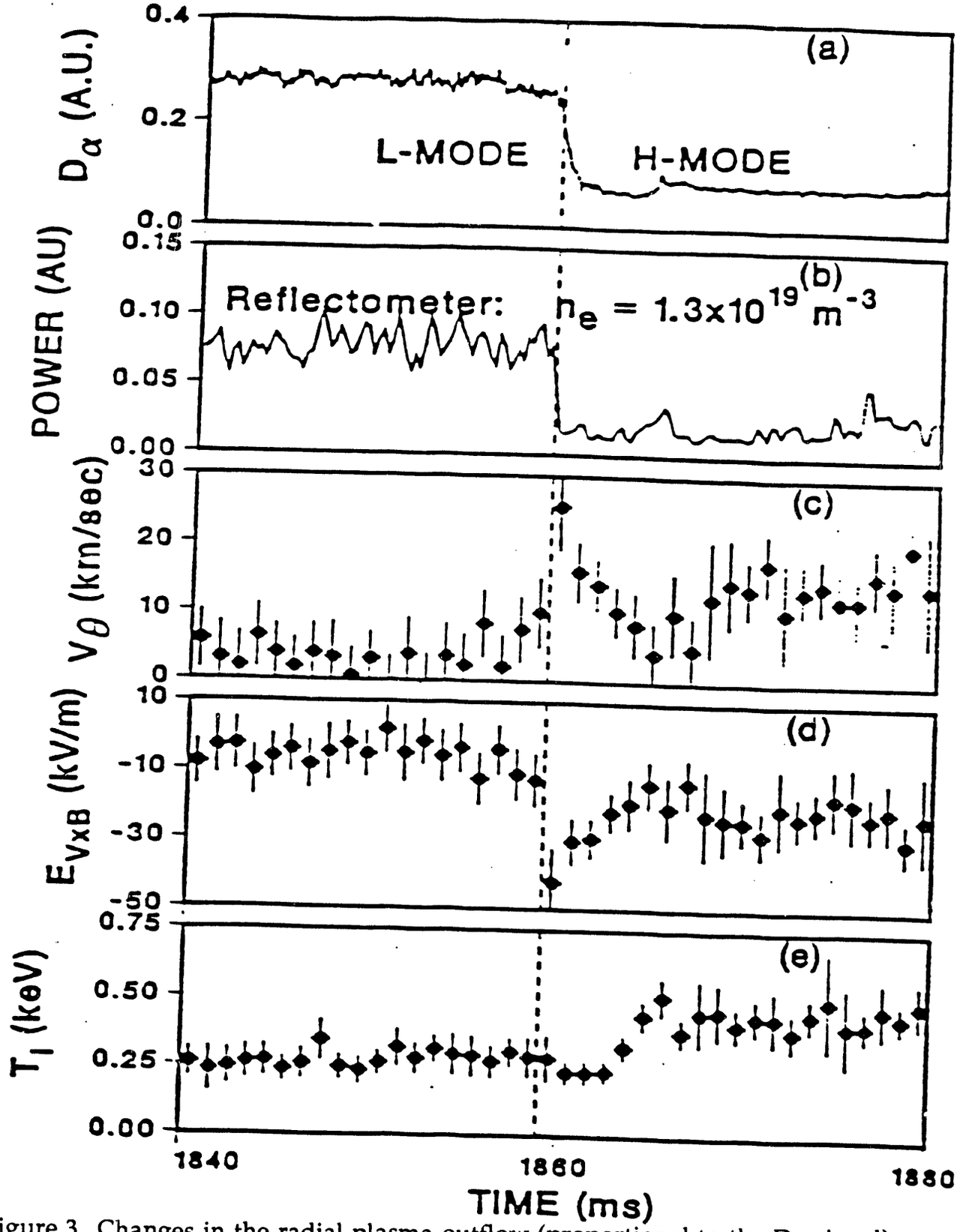

Figure 3. Changes in the radial plasma outflow (proportional to the D_α signal), fluctuations (reflectometer scattering power), edge poloidal flow, inferred electric field and ion temperature at an L-H transition occurring at about 1859 msec in DIII-D. The poloidal flow jumps up and the ion temperature remains unchanged while all the other signals decrease abruptly at the transition (from ref. 29).

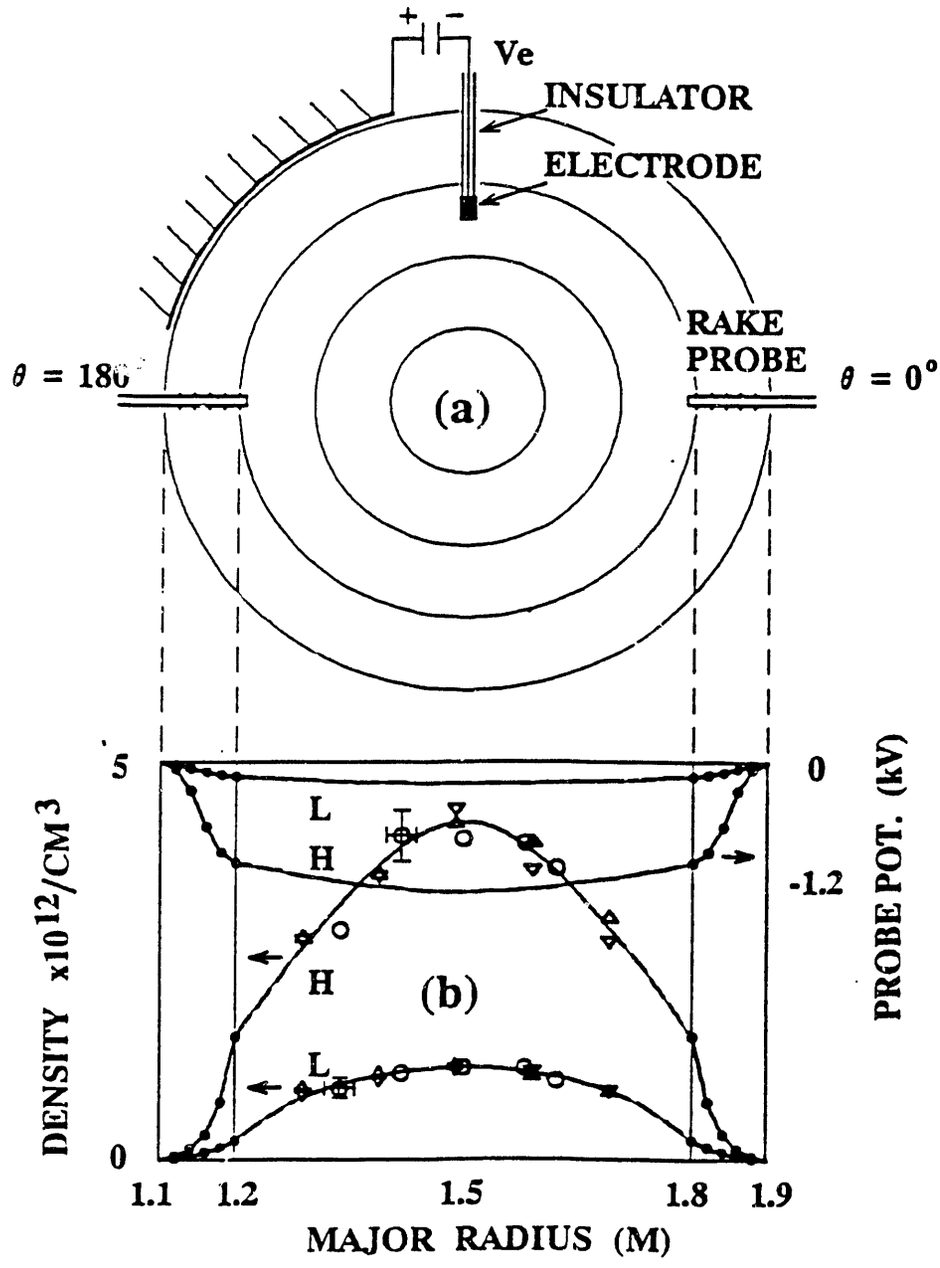

Figure 4. Production of an H-mode in the CCT experiment through negative biasing of a probe inserted into the plasma. The L-mode has a small negative potential throughout the plasma and modest density. The H-mode has a large negative electric field at the plasma edge, an edge density pedestal in this region, and much higher plasma density overall (from ref. 30).

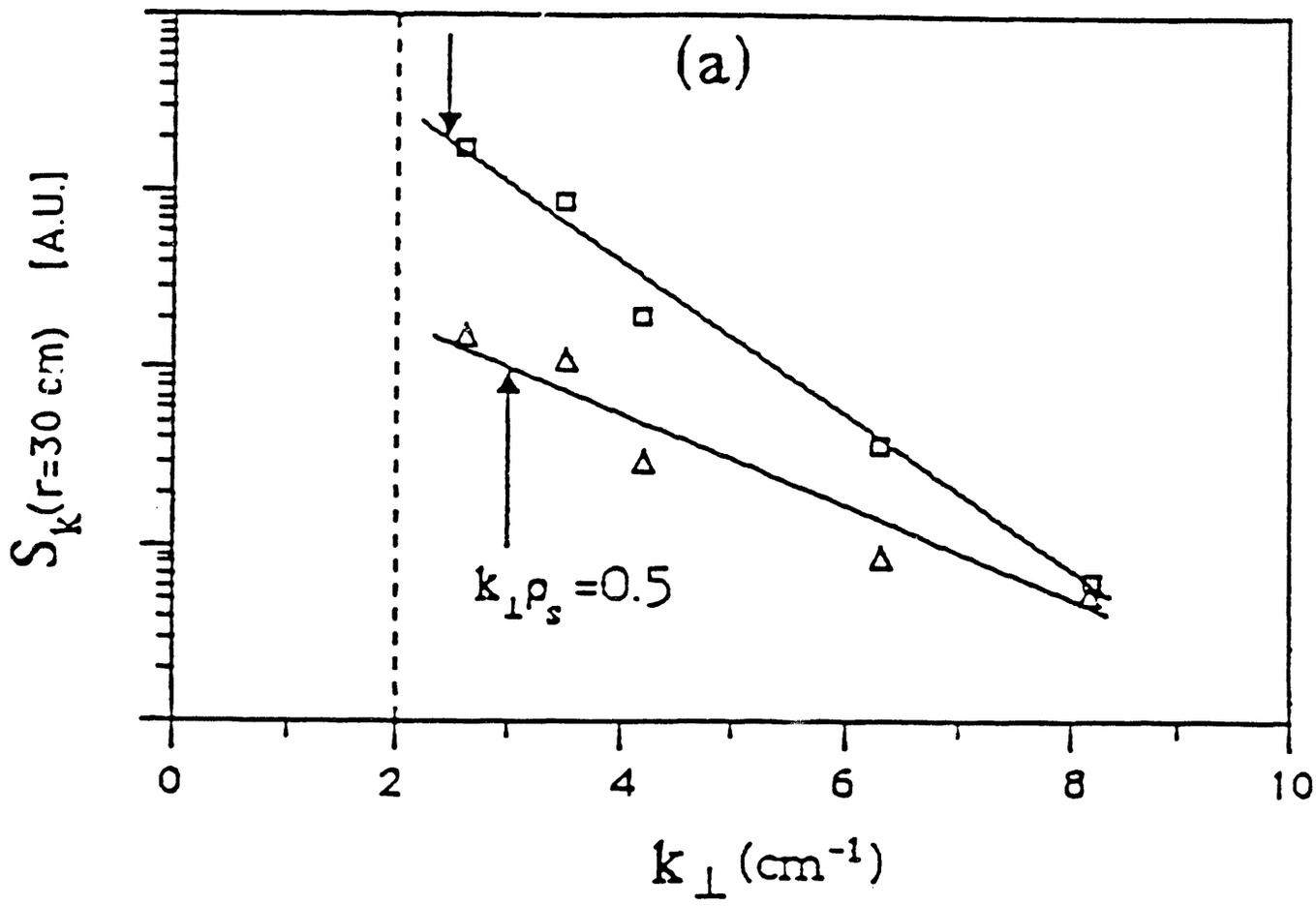

Figure 5. Microwave scattering power ($S_k \sim \tilde{n}_k^2$) as a function of the perpendicular wavenumber $k_\perp$. The lower line is for an ohmic plasma while the upper line is for a 9.1 MW neutral-beam-heated L-mode plasma. The region $k_\perp < 2\ cm^{-1}$ cannot be measured with the microwave scattering diagnostic, but is accessible with the newly developed HIBP, BES and CR diagnostics discussed in the text. Note that the lowest measurable $k_\perp$ fluctuations have the largest amplitudes and increase the most with auxiliary heating power (from ref. 37).

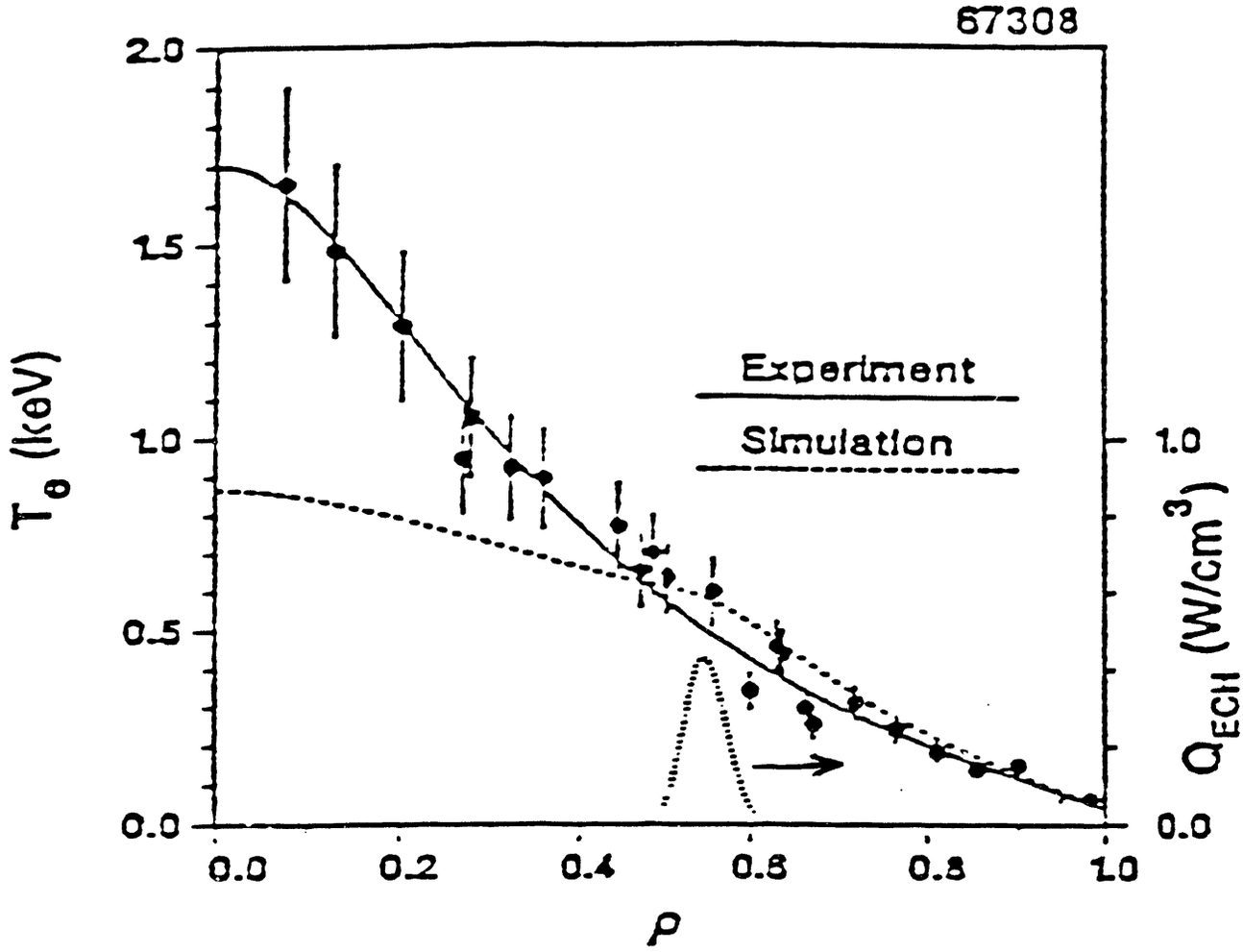

Figure 6. Electron temperature profile produced by strong off-axis ECH in DIII-D. The dashed simulation curve indicates the profile that would be expected from a purely diffusive model for electron heat transport for the indicated heating profile. Apparently more electron heat is reaching (via a heat pinch?) the central region than expected to produce the observed centrally peaked T_e profile (from ref. 92).

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