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Tokamak Turbulence - Electrostatic or Magnetic?

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Abstract. Anomalous transport in tokamaks is usually explained in terms of turbulent fluctuations. Predictions for the confinement properties of tokamaks would be placed on a more sound basis if the level of fluctuations and the resulting transport could be calculated. At present there is no clear agreement on whether the responsible fluctuations are electrostatic or magnetic. This paper discusses the existing evidence and arguments, both direct and circumstantial, that might help to resolve this question.

1. Introduction

The experimental fact that transport of energy and particles in Tokamaks often exceeds the predictions of neo-classical theory [1, 2] (e.g. χ_i by upto a factor 10, χ_e upto a factor 10^3), is usually assumed to result from the turbulent fluctuations of density, electric potential and magnetic field seen in tokamaks. It would clearly be helpful in constructing a model for anomalous transport if one was clear whether electrostatic or magnetic fluctuations (or both) were responsible. In this paper the evidence for and against either mechanism is gathered and the extent to which a judgement can be made is discussed.

2. Fluctuations

2.1. Observations

2.1.1. Density fluctuations Near the plasma edge density fluctuations can be detected by Langmuir probes and large amplitudes, $\delta n/n > 30\%$, are generally observed [1, 2] (Fig 1). In the plasma core, diagnostic techniques such as Micro-wave Scattering, Far Infra Red Scattering (FIR), Heavy Ion Beam Probes (HIBP), Beam Emission Spectroscopy (BES) and Reflectometry are now available [1, 2, 3]. Here the fluctuation levels are much lower [4], $\delta n/n$ <1% (Fig 2). The fluctuation spectra appear to correspond to broad-band turbulence with a width $\Delta\omega \sim 100$ kHz, but superimposed sharp features are occasionally observed [2]. Although some ambiguity in the absolute sign of the peak amplitude frequency in the spectra can arise because of Doppler shifts, the appearance of two separated features under certain conditions is indicative of the presence of both

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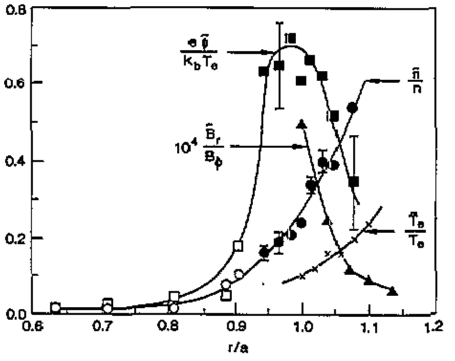

Figure 1. The spatial profiles of fluctuations near the limiter in TEXT.

electron and ion modes [5]. However, recent measurements [6] indicate the spread $\Delta\omega$ is largely due to Doppler shifts arising from sheared poloidal flows and the residual widths $\sim$ 5 kHz are comparable with long wavelength diamagnetic drift frequencies ω_{*e} with poloidal mode numbers $m \sim 30$. The wave-number spectrum $S(k_\perp)$ is dominated by long wavelengths [3, 4, 6, 7]. In the radial direction correlation lengths of 2 - 3 cm are observed with the spectrum peaking at the longest wavelength measurable. The poloidal spectrum is peaked in the region $k_\perp \rho_s \leq 0.3$, where ρ_s is the ion Larmor radius at the electron temperature, falling off as $S \sim k_\perp^{-3}$ at larger $k_\perp$. While $k_\perp$ scales with B consistently with $k_\perp \propto 1/\rho_s$, it does not appear to scale with T_e or the ion mass in the appropriate manner (e.g. ASDEX [8]). The fluctuation amplitudes satisfy the mixing length estimate $\delta n/n \sim 1/k_\perp L_n$ where L_n is the density scale length [9]. Typical parallel wavenumbers have $k_\parallel L \sim 1$ where L is a connection length around the torus, but evidence for ballooning structures is mixed [1, 2].

2.1.2. Potential fluctuations Probe measurements for these at the plasma edge (Fig 1) indicate similar features to those for δn although they differ from the Boltzmann value since $e\delta\phi/T_e > \delta n/n$ and their relative phase lies in the range $\pi/5 - \pi/2$. Measurements with the HIBP indicate $e\delta\phi/T_e \sim \delta n/n$ in the interior [1].

2.1.3. Temperature Fluctuations In tokamaks these have only been measured in the edge plasma (Fig 1) where fast Langmuir probes indicate $\delta T_e/T_e > 20\%$[1, 10]. It is interesting to note that $\delta T_e/T_e \sim 1\%$ has been reported in the core of the stellarator W7AS using a new technique of ECE Correlation Radiometry [11].

2.1.4. Magnetic fluctuations Until recently only measurements of magnetic fluctuations at the plasma edge by Mirnov coils have been possible (Fig 1). In addition to the coherent low mode number MHD signals such as sawteeth, fishbones and tearing modes, broadband fluctuations with amplitudes $\delta B_\perp/B \sim 10^{-4} - 10^{-5}$, having $\delta B_\perp \gg \delta B_\parallel$ and which are fairly isotropic in the plane perpendicular to $\boldsymbol{B}$, are observed [1, 2]. These small values appear to increase as one moves into the plasma (Fig 1) but no direct measurements were available until recently. However, the HIBP has been used on TEXT to measure core fluctuations during strong tearing mode activity, finding $\delta B_r/B \lesssim 10^{-2}$ in

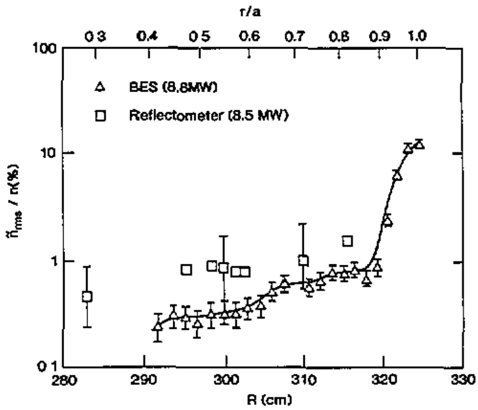

Figure 2. Amplitude of density fluctuations in a TFTR supershot plasma.

agreement with extrapolations from Mirnov coil measurements [12]. In addition a new technique, employing cross-polarisation scattering, has been applied to TORE SUPRA and preliminary results [13] suggest $\delta B_r/B \sim 10^{-4}$. These 'direct' diagnostics are supplemented by those inferred from other measurements. Thus LIDAR measurements on JET and TFTR suggest flat regions of width $\sim$ 10cm in the temperature profiles at the low order rational surfaces [14] (Fig 3), which have been interpreted as evidence for magnetic island structures or destroyed magnetic surfaces. This is supported by the H_α emission from pellets which indicates similar structures, with widths from a few mms to a few cms, in the q-profiles in TORE SUPRA [15]. However, ECE measurements in TFTR show no evidence for radial structures with extent exceeding 0.5cm; neither do Motional Stark Effect (MSE) measurements show signs of islands in the q-profiles [16]. In the RTP tokamak evidence for spatial inhomogeneities in Thomson scattering measurements of T_e was found in ECRH discharges. Specifically these were located in the central region where the power was deposited and could be interpreted as hot current carrying filaments of size $\sim$3mm, comparable with ρ_s [17].

2.2. Predictions

2.2.1. Electrostatic fluctuations There are a host of micro-instabilities predicted in a tokamak plasma, whose non-linearly saturated states could be responsible for the observations above [2]. Electrostatic drift waves are a prime candidate, particularly electron drift waves destabilised by trapped particles and ion temperature gradient modes. These linear modes would have appropriate frequencies $\sim \omega_*$, the sign of the frequency in the laboratory frame being characteristic of whether it is an electron or ion mode. Linear theories for drift waves predict maximum growth rates for $k_\perp \rho_s \sim 1$. However, recent developments have included the predictions of long radial structures covering macroscopic lengths, due to toroidal coupling [18], and simulations of long wavelength drift wave turbulence showing peaks at low-q resonances [19], offering an alternative to magnetic islands as an explanation for the plateaux seen in T_e profiles.

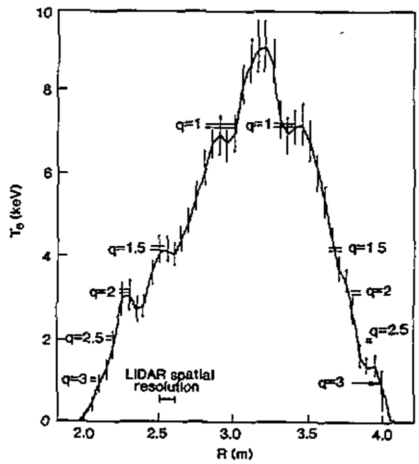

Figure 3. LIDAR T_e profile from JET showing large perturbations at rational q profile.

2.2.2. Magnetic fluctutations The situation for magnetic fluctuations is less clear. MHD theory is mainly concerned with low mode number instabilities, but shorter wavelength unstable resistive ballooning modes have been predicted and were thought to exist in ISX-B [20]. Drift waves will in general have a magnetic component and this becomes significant for those with $k_\perp \sim \omega_{pe}/c$ [21]. Since drift tearing modes appear to be linearly unstable only at high collisionality, $\omega_* < \nu_e$, most recent theoretical activity has been directed at non-linear tearing instability: modes that are only unstable because of the presence of turbulence or the existence of finite magnetic islands [22]. The natural stability of high m tearing modes can be overcome in these situations by a variety of non-linear effects: FLR, bootstrap currents, radiation, impurities and turbulent transport. Most of these mechanisms require a critical temperature gradient or β_p value to produce instability. (It should be borne in mind that there will in general also be electrostatic potentials associated with these islands.)

3. Fluctuation-driven Transport

The link between a turbulent fluctuation spectrum and transport can be subtle. For stationary turbulent electrostatic fluctuations a random walk estimate of $\boldsymbol{E} \times \boldsymbol{B}$ test particle diffusion is given by

$$D \sim \sum_k \left(\frac{k_\perp \delta\phi_k}{B}\right)^2 \tau_k \tag{1}$$

where τ_k is the correlation time for the steps. τ_k may be controlled by the linear particle motion: e.g. $\tau_k \sim L/V_\parallel$ for transiting particles; $\tau_k \sim 1/\nu_{\rm eff}$ for trapped particles, where $\nu_{\rm eff}$ is the effective collision frequency for scattering out of a trapped orbit. However, with increasing fluctuation levels it may be controlled by the turbulence itself: e.g. $\tau_k \sim B/k_\perp^2 \delta\phi_k$, the time to $\boldsymbol{E} \times \boldsymbol{B}$ drift across a perpendicular wavelength of the fluctuations. Consequently the dependence of D on $\delta\phi_k$ is only quadratic (ie quasi-linear) at lower amplitudes and becomes linear or even weaker when the Kubo number $K = k_\perp^2 \delta\varphi_k \tau_k / B \geq 1$ [23].

In the case of magnetic turbulence the Rechester and Rosenbluth formula for collisionless test particle diffusion is

$$D \sim V_\parallel \sum_k \left(\frac{\delta B_{r,k}}{B}\right)^2 L_k \tag{2}$$

Again the quasi-linear result only holds at low amplitude when $L_k \sim L_s$, the shear length; with increasing fluctuation level the correlation length L_k can be taken to be $\sim L_s/k_\perp W_k$, the 'island width' being given by $W_k \sim (L_s/k_\perp)^{1/2}(\delta B_{r,k}/B)^{1/2}$. A number of theories for magnetic fluctuations depend on the existence of magnetic islands in a sea of stochasticity. This limits the size of the islands, since they are destroyed when the stochasticity parameter $\alpha_s \geq 1$ (α_s measures the ratio of W_k to the separation of rational surfaces). With this constraint one is able to express D in the form [24]

$$D \sim \frac{V_\parallel R}{q^3 s^2}\left(\frac{r}{R}\right)^2\left(\frac{\alpha_s}{N}\right)^3 \tag{3}$$

where s is the shear parameter and N is the range of toroidal mode numbers of islands contributing to α_s. N may of course depend on plasma parameters, with implications for the ρ_* (normalised Larmor radius) scaling of such transport.

The test particle estimate (2) suggests that the more mobile electrons escape more rapidly and set up a positive ambipolar radial electric field. However, it is important to take account of the self-consistency effects arising from the charges and currents produced by the particles themselves. Thus the total particle fluxes Γ from $\delta\phi$ and δB are shown [25] to be automatically ambipolar when quasi-neutrality and Ampères equation are taken into account, irrespective of the radial electric field; it merely modifies the natural frequencies of the fluctuations. In fact the radial electric field, together with the toroidal flow, is controlled by the poloidal and toroidal viscosities, which may be neo-classical or anomalous.

The expression (2) for particle motion along a stochastic field also suggests that

$$\chi_i \sim D \sim \sqrt{\frac{m_e}{m_i}}\chi_e, \qquad D > D_Z, \qquad D_R > \chi_e \tag{4}$$

where D_Z are diffusion coefficients for impurities and D_R represents the loss rate of suprathermal electrons. However, finite drift orbit averaging effects can reduce transport of suprathermal electrons. Furthermore, when stochastic magnetic regions are embedded in regions of better confinement, the net transport can be strongly modified [26]. For example, if a fraction α of the plasma has good surfaces where the transport is due to electrostatic fluctuations with $\chi_{e,i} \sim \chi_0$, while the stochastic regions have electron transport characterised by $\chi_e^{\rm st} \sim A\chi_0$, then [26]

$$\chi_e^{\rm eff} \sim \frac{\chi_0(A+1)}{(\alpha A+1)}, \quad \chi_i^{\rm eff} \sim \chi_0 \frac{(A\sqrt{m_e/m_i}+1)}{(\alpha A\sqrt{m_e/m_i}+1)}$$

$$D_R^{\rm eff} \sim \chi_0 \sqrt{\frac{T_e}{E}}\frac{(A+T_e/E)}{(\alpha A+T_e/E)} \tag{5}$$

where E is the energy of the suprathermal electrons. Thus even small values for α can radically change the conclusions (4). If the transport in the 'good' regions is neo-classical then one can even have $\chi_i^{\rm eff} > \chi_e^{\rm eff}$. Finally, the test particle treatment still lacks some aspects of a fully self-consistent theory, namely inclusion of incoherent oscillations as in the theory of 'clumps'. Thus it has been demonstrated that in some situations pure magnetic fluctuations give rise to no net electron fluxes when ion dynamics is neglected; only the electrostatic fluctuations cause transport [27].

4. Correlations between Confinement and Fluctuations

4.1. Correlations with Electrostatic Fluctuations

4.1.1. The Edge In the edge region precise relationships between transport and electrostatic fluctuation can be established since probes can be used to measure amplitudes and phases of δn, $\delta\phi$ and δT_e. Following earlier work on CALTECH, MACROTOR, PRETEXT and TOSCA [1, 2], detailed studies have been made on TEXT [1]. For particle fluxes, magnitudes and scalings with B, I_p and n agree, indicating that the electrostatic fluctuations account for most, if not all, of them [28] (apart from uncertainties arising from poloidal asymmetries). A correlation between increased fluctuation driven fluxes and particle confinement with auxiliary heating in DITE (ECRH) has been shown [29]. The conductive electron heat flux is more uncertain, but recent measurements of δT_e [10] may be sufficient to explain it in terms of electrostatic fluctuations. Magnetic fluctuations are too small to play any significant part.

4.1.2. The core A clear correlation between τ_E^{-1} and $(\delta n/n)^2$ was seen in Ohmic, ICRF and NBI heated shots on TFR [30]. There are indications that $(\delta n/n)^2$ increases, whereas τ_E^{-1} decreases, on going from hydrogen to deuterium as working gas in ASDEX [8]. It is interesting to note that both τ_E and $(\delta n/n)^2$ are only weakly dependent on collisionality ν_* [31, 32].

Detailed studies of the correlation between density fluctuation characteristics and transport have been carried out recently. In TFTR, Ohmic, L-mode and Supershots have all been analysed using BES, microwave scattering and reflectometry [3, 4, 6, 7]. The fluctuation power is dominated by long wavelengths $k_\theta\rho_s \sim 0.14$ and this correlates with anomalous transport. Thus in the confinement zone it varies with $P_{\rm aux}$ and I_p consistently with τ_E and in L-mode current ramps the fluctuations change more rapidly at the edge than in the core, consistently with current penetration and heat transport changes. Calculations of χ based on (i) the strong turbulence estimate (1) using experimental fluctuation levels and (ii) random walk estimates $\chi \sim L_c^2/\tau_c$ using experimentally determined correlation lengths L_c and times τ_c, are in good agreement with power balance calculations [3] (Fig 4). The fluctuation scale length also decreased from $\sim$ 4cm in low density Ohmic plasmas to $\sim$2cm in Supershots, consistently with the improved confinement. The longer wavelength fluctuations observed in L-modes may relate to the Bohm-like scaling of L-mode confinement [31]. It is interesting to note that the radial profiles of $(\delta n/n)^2$ and χ increase with radius together in the core.

In DIIID and ASDEX detailed correlations between fluctuation levels and L-H transitions have been observed [33] (Fig 5). As the edge transport barrier forms, the

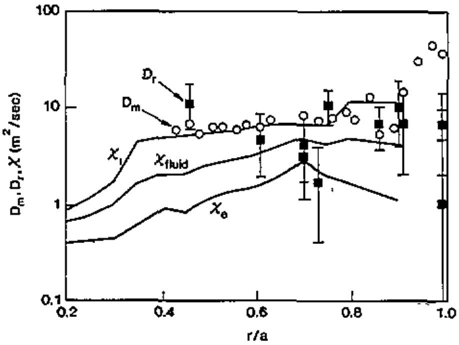

Figure 4. Thermal diffusivities determined from power balance in a TFTR supershot compared to diffusivities inferred from BES measurements; D_m is a strong turbulence estimate and $D_r = L_c^2/\tau_c$ is a random walk estimate.

fluctuation level drops almost simultaneously (within 100μs) and furthermore the improved confinement that develops later for $r/a \gtrsim 0.7$ is accompanied by a decrease of fluctuations over 10's ms.

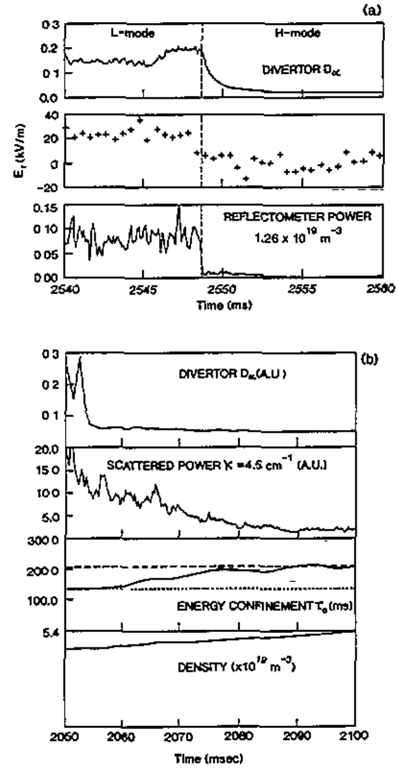

Figure 5. The correlation between fluctuation levels and the L-H transition in DIIID: (a) at the edge, (b) at the interior.

Ohmic discharges in TORE SUPRA [34] also show a correlation between χ_e and $(\delta n)^2$ (Fig 6) and indeed indicate that the higher density Saturated Ohmic Confinement (SOC) is associated with an increase in χ_e, not in χ_i. Neither is it associated with the onset of ion turbulence. This runs counter to the explanation that SOC is explained by the onset of η_i-mode turbulence, motivated by (i) the observation of Improved Ohmic Confinement (IOC) when pellet fuelling, rather than gas puffing, is used to achieve higher densities and (ii) correlations of these fuelling techniques with the appearance of an ion feature in TEXT fluctuation spectra [5].

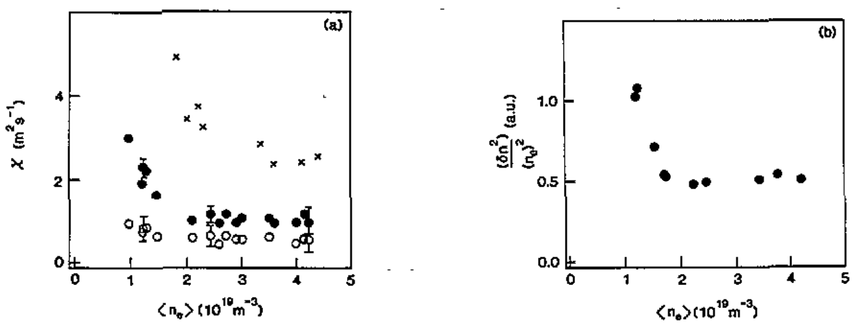

Figure 6. The correlation between (a) χ_e (black points) and (b) density fluctuations in TORE SUPRA. Also shown in (a) are χ_i (circles) and χ(heat-pulse) (crosses).

It has been possible with HIBP in TEXT to determine $\delta\phi$ and δn and their phase relation, allowing a proper evaluation of the particle flux Γ from electrostatic fluctuations and there is approximate agreement over the region $r/a > 0.6$ where $\Gamma \neq 0$, but errors are large [35]. Since δT has not yet been measured in the core, reliance on theoretical models for the phases is necessary to calculate a heat flux from $(\delta n)^2$. The most popular theoretical model, the Dissipative Trapped Electron Mode, yields smaller heat fluxes than those deduced from power balance unless values $k_\theta \rho_s \sim 0.4$, rather than the measured $k_\theta \rho_s \sim 0.1$, are used [35].

4.2. Correlations with Magnetic Fluctuations

There are clear connections between gross MHD behaviour and transport [1]: the saw-teeth expel energetic particles and impurities from the plasma centre, the fishbones expel energetic ions, ELMS provide an edge loss mechanism, χ increases at the β-limit (e.g. ASDEX [36]) and strong tearing mode activity produces magnetic islands which can short-circuit the confinement.

However, the correlation between broadband magnetic fluctuations and transport is less obvious. Direct measurements are usually only possible at the edge [1]. There is no clear correlation between these edge fluctuations and core confinement. TOSCA (in the Ohmic phase) and TFR (in L-mode) show none, whereas JET [37] and ISX-B (both in Ohmic and L-mode) do; indeed, high-β_p confinement in ISX-B has been interpreted in terms of high-n resistive balloning modes [20]. DIIID shows a correlation between different confinement modes and the magnetic fluctuation level [38] (although one would not expect the improved particle confinement in H-mode to be affected by $(\delta B)^2$).

The edge fluctuations are too small to account for edge fluxes and the indications of their interior profiles are inconsistent with the radial profile of χ; they may be merely driven by electrostatic fluctuations, e.g. DITE [39]. However, estimates of core transport based on assuming the plateaux in the temperature and q-profiles are indeed magnetic islands give plausible values for χ_e [15].

5. Signatures for Electrostatic and Magnetic Transport

One possible signature of magnetic transport is a β dependence of τ_E and χ but the evidence is varied. Thus L-mode scalings can be expressed in the form $\tau_E \sim \tau_{\mathrm{Bohm}}\beta^{-1/2}$ [31] which is suggestive of some magnetic mechanism. Studies of the scaling of χ in Ohmic and L-modes in TFTR shows an initial increase with β followed by a regime independent of β whereas in DIIID no dependence on β was exhibited [40]. ASDEX indicates $\chi \sim \beta^{-1/2}$ in Ohmic, becoming $\chi \sim \beta^{1/2}$ in L and H-mode [41].

Simple mindedly, the negative radial electric fields observed in the plasma core would argue against magnetic transport but, as noted in Section 3, the sign of the radial electric field is not necessarily significant for self-consistent fluctuations. (When stochastic magnetic fields are set up by external perturbations, a positive radial electric field is observed as expected, e.g. TEXT [42].)

Experimentally the ratios of χ_i, χ_e, χ_ϕ, D and D_Z vary between Ohmic (LOC and SOC), L and H-modes and Supershots, but generally speaking $\chi_\phi \sim \chi_i \geq \chi_e$, $D \sim D_Z$ and $\chi_e/D \sim 3-8$ which is broadly consistent with electrostatic, rather than magnetic, transport (cf eqn (4)).

The more rapid motion of suprathermal electrons along stochastic fields offers a possible useful probe to investigate the role of magnetic fluctuations in transport. Techniques to estimate D_R for energetic particles include applying a perturbation to remove them (e.g. a pellet) or a modulation of their source (eg LCHD) and inferring their diffusion from the recovery time for a signal associated with them (e.g. X-rays, ECE). Evidence varies [43]: JET [44] indicates poorer confinement ($D_R \sim 10\mathrm{m}^2\ \mathrm{s}^{-1}$) for fast electrons, as might be expected from magnetic fluctuations, while ASDEX [45, 46] (in Ohmic and LHCD), RTP [47] (ECRH) and recently TORE SUPRA [48] suggest the opposite ($D_R \lesssim 0.5\mathrm{m}^2\ \mathrm{s}^{-1}$), consistent with transport from electrostatic fluctuations. However, it may represent the effects of finite orbit averaging, with different correlation lengths for turbulence in different machines.

ASDEX has shown that bulk and runaway confinement, τ_E and τ_R respectively, are correlated with each other during L-mode power scans and in OH→L and L→H transitions. They are also correlated with the core $(\delta B)^2$ inferred from runaway confinement, and a 1mm radial correlation length for the turbulence can explain the observed ratio τ_R/τ_E [45]. In TEXT, a radial profile for $D_R(r)$ has been deduced but the $(\delta B)^2$ inferred are insufficient to explain τ_E, since orbit averaging effects are small [49] (Fig 7).

An alternative diagnostic is to calculate the steady state electron distribution including sources and radial diffusion and then comparing the resulting X-ray spectra with experiment. The Fokker Planck code BANDIT has been applied to data from ST and CLEO with the conclusion that the 'warm' energetic particles are better confined than

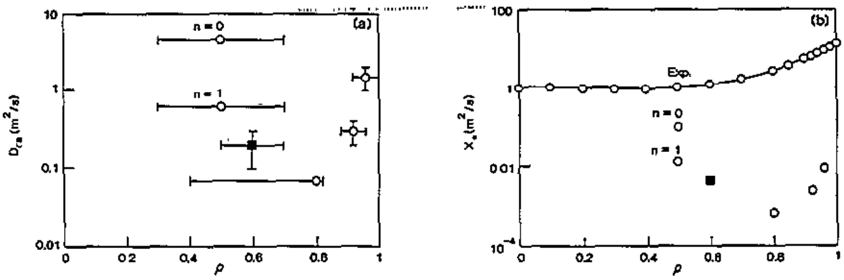

Figure 7. Runaway diffusivity and the implied thermal diffusivity due to magnetic fluctuations from TEXT.

the bulk [43]. Since orbit effects are less important for these than for runaways, this argues in favour of electrostatic turbulent transport. However, indications from modelling ECE emission in DIIID favour magnetic transport [50].

6. Physics Models for Confinement

The success or otherwise of physics based transport models provides an indirect test of transport mechanisms. Ohmic scalings $\tau_E \sim n$ have stimulated models based on collisionless skin-depth turbulence, which has an electromagnetic component, as well as electrostatic turbulence due to the dissipative trapped electron drift instability or collisionless drift instabilities (when the density scaling appears through a correlation with $Z_{\rm eff}$ in Ohmic heating [51]).

The power degradation observed in L-mode could, in principle, be explained in terms of electrostatic drift wave turbulence. However, it has proved difficult to explain radial profiles of transport coefficients and to a lesser extent the favourable current scaling with such models. (There are now indications that L-mode diffusivities are Bohm-like [31], whereas most drift-wave models lead to gyro-Bohm scalings, so unless long wavelength [19] or long radially coherent structures [18] exist, this poses a problem.) The H-mode edge transport barrier is claimed to be associated with the role of radial electric fields in suppressing electrostatic turbulence [33].

Resistive ballooning models of the Carreras-Diamond type are dominantly electrostatic but drive a magnetic component causing stochastic field transport; they have been invoked to explain L-mode power degradation [20], the current scaling and edge transport - a recent version appropriate to higher temperature by Itoh et al [52], gives a reasonable description of many features of L-mode transport. Magnetic islands do exist theoretically as non-linear instabilities at higher β_p values [22], (e.g. the bootstrap driven islands appear endemic [53] and Kadomstev has proposed another robust mechanism [54]) and could well account for the L-mode power degradation. (It should be noted that the Rebut-Lallia-Watkins model [55] is semi-empirical in nature and does not have any particular characteristics that one might associate with magnetic turbulence, although the stochastic threshold is invoked as a reason for a critical gradient. This model also suffers from the criticism that it is gyro-Bohm in nature.) The frequent claim that stochastic field diffusivities are independent of gyro-radius is too simplistic

- the fluctuation levels themselves or the value of N in eqn (3) are likely to depend on microscopic lengths unless driven by error fields and toroidal couplings.

Difficulties associated with radial profiles of thermal diffusivities may indicate the presence of critical gradients for marginal stability or the existence of radial pinches; these may also disguise the scalings associated with the diffusivities. Particle and impurity transport [56] and off-axis heating [57] all suggest such pinches, but most models have difficulties with these, It is interesting to note that Taylor has suggested that the natural current profiles of tokamaks could be associated with the existence of current filaments throughout the plasma and that the transport generated by these magnetic structures could cause particle and heat pinches [58].

7. Conclusions

There are situations of strong low mode number MHD and tearing mode activity when magnetic fluctuations are clearly important for confinement.

However, in other situations the evidence favours electrostatic fluctuations as the cause of transport. Thus there is strong evidence for a correlation between the $(\delta n)^2$ fluctuation spectrum and the overall confinement τ_E and particularly with details of the local χ in the core. This is true of responses to transients such as L-H transitions and current ramps as well as correlations with different confinement regime. Edge confinement appears to be well described by electrostatic fluctuations, but this may be uncorrelated to the core. Theories based on electrostatic turbulence predict many characteristics of the observed fluctuations and the ratios of various transport coefficients but have difficulties with some scalings and radial profiles of transport coefficients.

Evidence in favour of magnetic fluctuations is more circumstantial or mixed. Global energy confinement scalings appear to deteriorate with β, though this is not always the case for β scans of χ. Inferences from suprathermal particles vary but the balance favours electrostatic fluctuations as the cause of transport. Measurements of $(\delta B)^2$ in the core are in their infancy. It is tempting to interpret the flat spots in temperature profiles observed by some diagnostics in terms of magnetic islands but evidence from other diagnostics conflicts with them; interpretations in terms of electrostatic fluctuations are also possible. It is premature to believe observations of filaments are universal despite their attractive association with theory.

However, the question may not be well posed: there remains the possibility that there are mixed regions of electrostatic and magnetic driven transport, with the former readily 'hiding' some of the signatures of the latter, e.g. fast particle transport; alternatively, electrostatic fluctuations observed may be generated by magnetic islands, ie the fluctuations are truly electromagnetic and no real distinction exists.

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