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Electrostatic Turbulence and Anomalous Transport

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Abstract

Anomalous transport produced by electrostatic turbulence using invariance principles/dimensional analysis can produce scaling laws for confinement similar to the empirical results deduced from experimental data particularly if geometrical effects in toroidal geometry are allowed for. The ion mass dependence however remains a problem for most theories. Experimentally there is good evidence in both ohmic and additionally heated tokamaks that the particle transport in the outer regions of the plasma is driven by electrostatic fluctuations but the position on energy transport is more complicated due to incomplete data on temperature fluctuations. Due to the lack of good diagnostic techniques to measure particle and heat fluxes driven by fluctuations in the hot core of the plasma it is less certain that electrostatic fluctuations produce the anomalous transport in this region. However the magnetic fluctuations which arise simply from pressure balance are large enough (at high beta) to produce a significant contribution to anomalous heat transport in the core but not at the edge of the plasma.

Introduction

The potential of tokamaks, pinches and stellarators and other magnetic confinement systems as fusion reactors depends crucially on understanding and predicting the energy confinement properties. Unfortunately at present there is no satisfactory model for explaining the anomalously large energy, particle and momentum transport observed in these experiments, which for example in the case of electrons can be up to two orders of magnitude greater than the predicted classical or neoclassical transport theory. In addition there are also substantial anomalies for the ions. The magnitude and the scaling of the energy confinement time in both ohmically and additionally heated tokamaks, which seems to be independent of heating source, differs appreciably from the theoretical predictions of neoclassical theory.

Many workers have sought explanations in terms of anomalous transport due to turbulent fluctuations of electromagnetic fields within the plasma: however there is work by a number of scientists that has in fact achieved considerable success, eg Woods [1] with models based on classical

Coulomb collisions together with a 'second order' theory based on a kinetic equation involving ingredients which differ from the more conventional treatments. Nevertheless it is an experimentally observed fact that fluctuations at a substantial level are observed in all our toroidal magnetic confinement systems, which do appear to drive particles and energy across the magnetic surfaces.

From models of the transport associated with the fluctuations, it is possible to derive expressions for the confinement time scaling which are based upon nonlinear saturation levels and correlation times of the fluctuations associated with a variety of plasma instabilities. Though these can produce some features of the experimental scalings, eg Waltz [2], they usually require extra ingredients to be inserted to explain other aspects of the scalings. For example, drift wave models usually require additional transport in the outer regions of the plasma, though this might arise from toroidal effects such as in the $1 + q^2$ factor for Pfirsch-Schluter diffusion for particles. Many models can quite satisfactorily explain global confinement scaling but are quite unable to predict sufficient transport near the centre of the plasma or periphery. This is a more critical test of the theories, ie their ability to reproduce the local heat fluxes as a function of radius.

Regimes of improved confinement, ie H modes, require a model to predict reduced transport in the presence of separatrix geometry. A further constraint on the theories is their need to explain localised and transient phenomena, such as are generated by sawteeth and for example by modulated electron cyclotron resonant heating. These can potentially yield substantial information on thermal diffusion and particularly on the off-diagonal elements of the transport matrices.

Tests of a theoretical model depend on whether the features of the associated turbulence (e.g. saturation levels, spectra, energy cascade etc) can be detected experimentally and are correlated with transport phenomena. The fluctuation spectra tend to lie in the region with wavelengths comparable to the ion gyro-radius and frequencies comparable to the diamagnetic drift frequencies. At first sight this might be considered to be consistent with drift wave turbulence, however the observation, at least in the outer regions of the plasma, of a non-Boltzmann electron response, i.e. $\tilde{n}/n < e\tilde{\phi}/T_e$ tends to pose difficulties for such theories. However it should be noted that in the core of the plasma, and in some cases at the edge, the electron response is close to Boltzmann-like, particularly after fluctuations in the temperature are allowed for. The frequency spectrum is in general broad indicating strong turbulence rather than normal modes.

There are a variety of approaches which are appropriate and have been pursued quite actively, in particular:- marginal stability, dimensional arguments and invariance techniques which are very powerful for global scaling, upper bounds, quasilinear approaches, theories of the turbulent spectrum, test particle theories, and numerical simulation.

Scaling laws

A variety of scaling laws of an empirical nature are now available such as neoAlcator [3] and Goldston [4] scaling, which allow us to predict the size and currents needed for a reactor. Unfortunately there are now many such scalings and their predictions for plasma current vary dramatically from ~ 6 MA to 30 MA. These scaling laws tend to encompass a variety of experimental biases associated with the ability and ease to achieve certain modes of plasma operation and perhaps do not reflect the full range of physical processes involved in confinement. It is far more reasonable to ascribe the basic mechanism to a variety of physical processes which through invariance principles or dimensional analysis [5] allows us to parametrise the dependence of the global confinement time. For a collisionless low beta plasma $\tau \sim B^{-1} f(T/a^2B^2)$ whereas for an ideal MHD plasma $\tau \sim B^{-1} na^2 f(\beta)$. In terms of dimensionless parameters ($\beta, \rho/a, \lambda/a, \lambda_D/a$ i.e. normalised Larmor radius, normalised mean free path and Debye length), we can characterise drift waves in terms of Larmor radius and mean free path so that $\tau \sim B^{-1} f(T/a^2B^2, n a^2/B^4a^5)$. For collisionless trapped electrons the function is the inverse three halves power of T/a^2B^2 and yields $\tau \sim a^3 B^2/T^{3/2} \mu^{1/2}$ where μ is the ratio of ion to proton mass. If we replace the temperature with the input power, P, then the confinement time $\tau \sim a^3 B^{4/5} (n/P)^{3/5} \mu^{-1/5}$ ie degrades with power. This does indicate some of the confinement time scalings that are observed, however such a theory does not account for which component of the magnetic field is present or detailed geometric effects. It has been argued, by Lackner, that the field in such an expression might well be the poloidal field associated, with trapped particles being deflected from their orbits [6] due to some anomalous process. In this case a global confinement scaling law is obtained which compares satisfactorily with experimental results (apart from the mass dependence) and allows one to extrapolate using physical variables to future facilities. A less satisfactory scaling which gives degradation with power, a more correct mass dependence, and a dependence on the current, is given by an ideal model with the poloidal Alfven transit time.

Such an approach can be exploited further to predict the performance of specific devices which have the same Connor-Taylor parameters. For example in an ohmic discharge these would be na^2 and $a^5 B^4/Z$ but the other characteristics of the device must be similar (eg aspect ratio safety factor, isotope, plasma shape). In this case the confinement time scales as B^{-1}. It is clear that certain physical processes such as alpha particle heating, Bremsstrahlung and synchrotron radiation cannot be modelled in this way. Nevertheless the technique can be checked by comparing discharges in a device such as FT at high field with those on ASDEX at a more modest field and it would seem to be borne out. This implies that boundary conditions and impurities do not play an important role in the confinement process. The technique is sufficiently powerful that all time constants should scale as 1/B so that the sawtooth period in FT with similar q, isotope etc can be compared with the period on ASDEX and this is also borne out by observation e.g. 5ms and 12ms for 6T and 2.5T respectively. Using the same technique it is possible to predict the parameters of IGNITOR from those obtained on JET and to conclude that ohmic triple product, n T τ, will be 3 times better on IGNITOR.

Turbulent Transport

The source of free energy available to drive a wide range of instabilities in magnetically confined plasma derives from the inhomogeneities in field, current, density, temperature and flow which can set up a wide spectrum of modes within the plasma. These modes then interact by resonance broadening, island overlap etc to establish fluctuation spectra which both through dissipation mechanisms at high and low wave numbers and nonlinear interactions leads to a saturated fluctuation level with appropriate correlation times and frequencies. These saturated fluctuations then, through for example, mixing lengths, coherent structures and superthermal behaviour, lead to a transport matrix for which the thermal diffusivity, particle diffusivity etc set up the global balance in determining the gradients of field, density, temperature etc. The closure is demonstrated in Figure 1. A particularly important point to

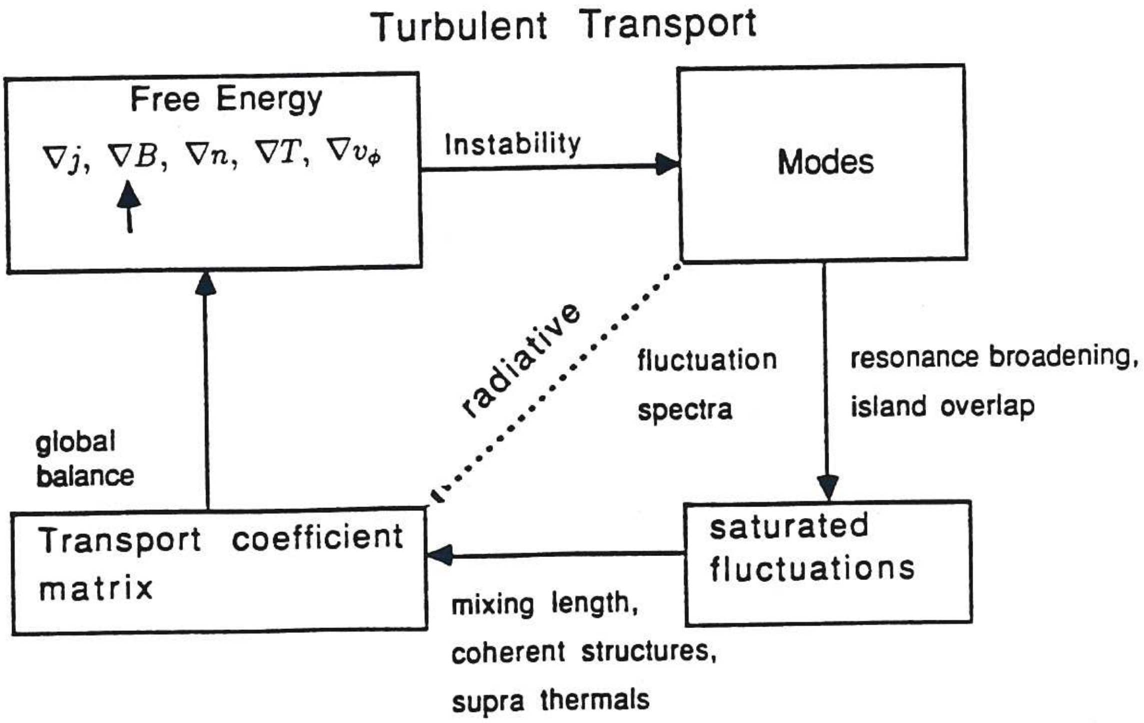


Figure 1 Closure of the turbulent transport problem

note is that mode interactions in toroidal geometry can short out the diffusive process associated with localised turbulent fluctuations through toroidal coupling. This process is particularly apparent in tight aspect ratio non circular tokamaks with the internal mode activity coupled to the edge of the plasma thereby shorting out the diffusive processes and providing transport which cannot be described in the usual manner. A second example is radiative transport associated with non thermal behaviour of particles which leads to cyclotron emission from the hot non thermal core of the plasma and reabsorption in the outer regions. This type of transport is expected to be quite important in thermonuclear plasmas but may well already manifest itself in some non thermal discharges in present devices.

Electrostatic fluctuations in the confinement region

Unfortunately the diagnostic techniques available for measuring the internal fluctuations, density, potential, magnetic field, and temperature are rather poor at present. Only the heavy ion beam probe technique permits measurements of density and potential simultaneously in the core and then only in a rather restricted parameter range.

The first experiments to explore the internal fluctuations in magnetic confinement systems were those using microwave scattering eg as used on the ZETA and ALPHA devices originally and then later on the early tokamaks, ATC, TFR etc. These were then followed by laser scattering experiments using CO_2 and far infrared wavelengths. Most of the information that we have is on density fluctuations. The turbulence is characterised by a broad spectrum in frequency and wave number with the width of the frequency spectrum being approximately equal to the mean frequency of the turbulent perturbations which is approximately at the electron diamagnetic drift speed.

A perhaps somewhat surprising feature borne out by many tokamaks is that the amplitude of the density fluctuations is closely approximated by the mixing length formula, $\tilde{n}/n \sim 1/\bar{k} L_n$ where L_n is the density gradient scale length. As Figure 2 shows, this is borne out by quite a wide range of high and low field tokamaks of differing sizes. Although most devices fit this type of scaling there are some exceptions, eg TFR. The mean wave number is found to be proportional to toroidal field from 0.2 - 10T and this might indicate that it is related to Larmor radius, however in most cases no actual temperature dependence is found, though again there are exceptions.

Fluctuations are found to be close to 2-dimensional with the parallel wave number much less than either radial or poloidal wave numbers. The fluctuations are found to be a strong function of minor radius with core

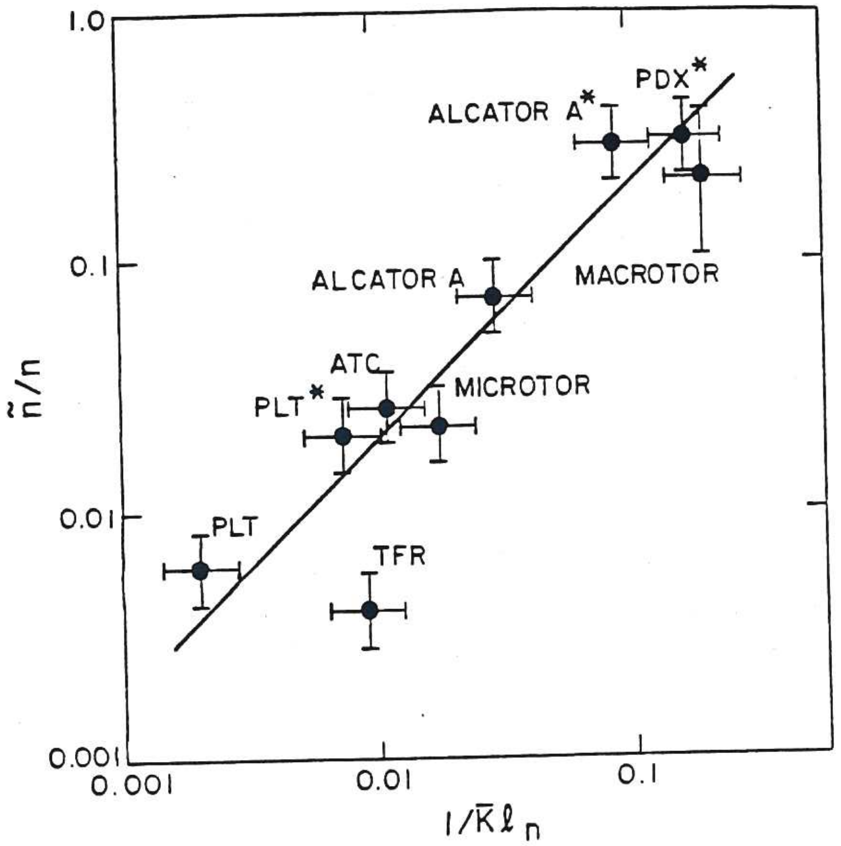


Figure 2 The amplitude $\tilde{n}/n$ of the density fluctuations in various tokamaks is shown as a function of $1/\bar{k}L_n$. Asterisks indicate measurements closer to the plasma edge. As a guide to the eye, the solid line corresponds to $\tilde{n}/n = 2/\bar{k}L_n$.

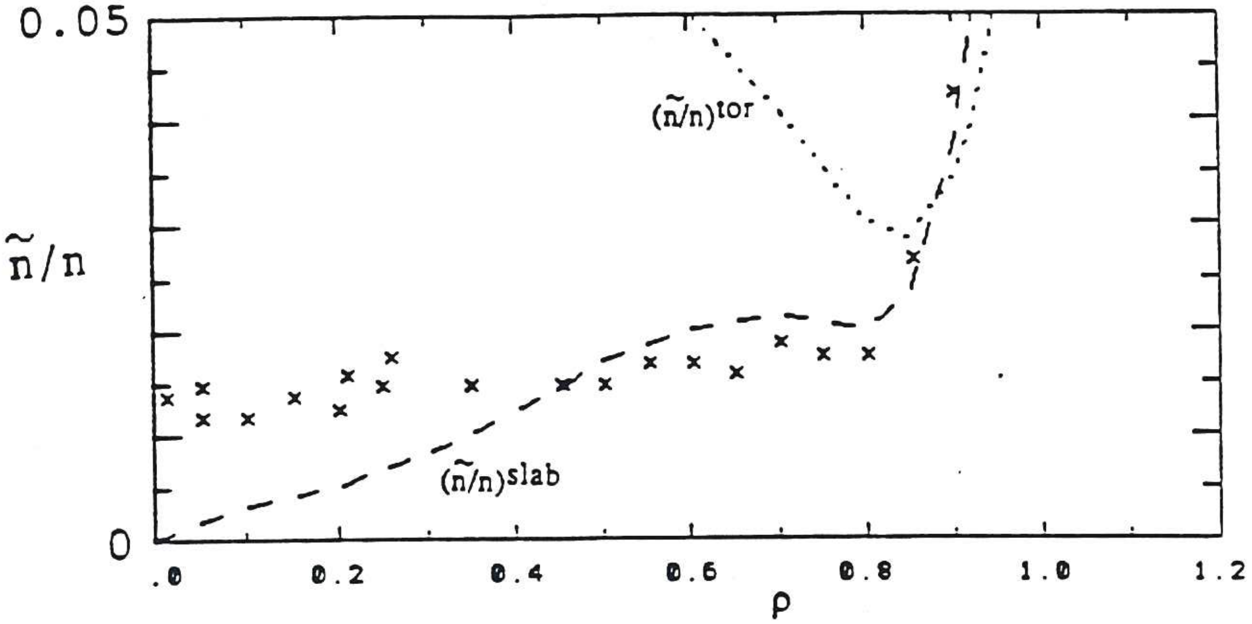


Figure 3 The spatial variation of n/n from TEXT (B_ϕ = 2T, I_p = 200 kA, n_e = 2 to 3 x $10^{19}m^{-3}$, H+), shown as crosses (HIBP). Also shown are the predictions of two mixing length estimates, $(\tilde{n}/n)^{tor}$ and $(\tilde{n}/n)^{slab}$. Both electron feature $\tilde{n}$ /n and k_θ ($k_\theta \rho_s$ = 0.1) are interpreted assuming no ion feature is present.

fluctuations varying down to as little as 1% or less and the edge fluctuations rising to as much as 50%. This radial variation is shown for the heavy ion beam probe diagnostic measurements on TEXT in Figure 3 where it is possible to see that the density fluctuations remain at a low level throughout the major confinement region of the plasma. The fact that the edge fluctuations are so large makes it difficult in many cases to be sure that the internal fluctuations of density have been measured correctly and are not dominated by the strongly turbulent outer annular ring. The fluctuations are found to be characterised by $k\rho_i \sim 0.1 - 0.5$.

In the core the fluctuations are usually observed to propagate in the electron drift direction when allowance has been made for plasma rotation. A particularly interesting point to note is that the characteristics of the fluctuations are found to be the same in both reversed field pinches and stellarators; which would seem to indicate a common origin rather than one associated with magnetic geometry.

For ohmically heated plasmas both in stellarators and tokamaks the amplitude of the density fluctuations normalised to the mean density is found to be weakly dependent on density. This is shown in a striking way for the ASDEX device in Figure 4 where the amplitude of the fluctuating power in the density fluctuations follows very closely the mean rise in average density over a time interval of about 1 second. This observation

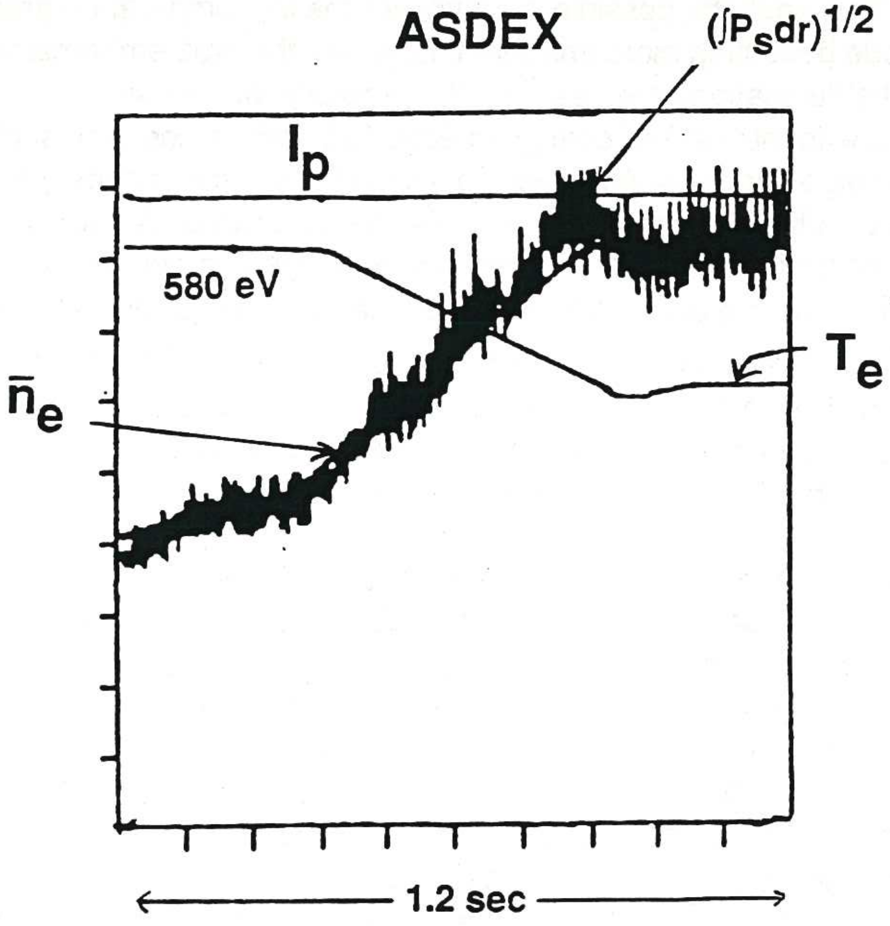


Figure 4 Density scaling of the rms scattering signal $(\int P_s)^{1/2}$ for a discharge in which there is a density ramp and 2 plateaus ($k_\perp = 3\mathrm{cm}^{-1}$, $r = 0\mathrm{cm}$).

is fairly common throughout most of the tokamaks investigated and is also borne out by probe fluctuation measurements near the edge, seeming to indicate that the density fluctuations are unrelated to the ohmic confinement scaling.

Turning to additionally heated plasmas it is found that the density fluctuations amplitude increases and there would seem to be some correlation with confinement. However it should be noted that with strong electron cyclotron resonant heating even when there is an enhanced trapped electron population present there seems to be little or no increase in the core density fluctuations. The correlation between confinement and density fluctuations was particularly marked on the TFR device [7] both with ion cyclotron resonant heating and neutral beam injection.

There are a number of difficulties with the measured fluctuations, in particular there are asymmetries both in/out (as one might expect from toroidal behaviour) and up/down which could be associated with drift effects. As the density is raised either by gas puffing or pellet refuelling, then the form of the power spectrum of the fluctuations changes as observed on TEXT and JIPPT II-U. At low densities it is predominantly in the electron drift direction but as the density is raised there is a shift in the spectrum with a feature appearing in the ion diamagnetic drift direction. This could be possible evidence for the ion temperature gradient driven mode becoming more important. However the problem remains as to whether the fluctuations are free from the problems of inversion associated with the marked change in edge fluctuations and their spatial position at high densities. A further problem is the ion mass dependence which is not exhibited very clearly on some devices but on ASDEX there is a marked shift of the scattered power to lower wave numbers in moving from a hydrogen to a deuterium discharge, i.e. $k \rho_i \sim$ constant with the scattered power at small wave numbers increasing for D. This seems to be in the opposite direction to confinement scaling. On separatrix controlled tokamaks there is clear evidence that the total scattered power signal decreases substantially in the L to H mode transition.

Unfortunately there are very few measurements of other fluctuating quantities in the core of the plasma and indeed there is no real reason why the amplitude of the density fluctuations alone should be correlated with confinement. There are some potential fluctuation measurements using the heavy ion beam probe which seem to indicate that in the core of the plasma, the fluctuations are much closer to Boltzmann-like than observed at the edge of the plasma. This does allow particle fluxes to be measured further into the plasma. However these become very small which gives rise to long particle confinement in the core of the plasma. Thus there is no direct measurement of the particle or energy fluxes associated with fluctuations in the turbulent core of a high temperature magnetically confined plasma so far.

Edge Region

In this case nearly all the fluctuating quantities can be measured simultaneously and spatially resolved in particular, density, potential, electron temperature, magnetic field, however at the moment there are no ion temperature fluctuations which are particularly important, in for example elucidating whether ion temperature gradient driven turbulence is important. The temperature fluctuations can be measured by using a technique developed many years ago on the ZETA device using Langmuir probe characteristics [8]. This technique indicates that the temperature fluctuations in the outer regions of a tokamak can vary from nearly isothermal eg TOSCA, to closer to adiabatic eg TEXT and DITE. In the outer regions the total heat and particle fluxes can be compared with the fluctuation driven ones, Figure 5 shows for the DITE device the radial variation of the magnetic field, density and potential fluctuations, using a reciprocating probe which minimises the perturbation to the plasma. It is important to note that the magnetic fluctuations increase as one moves into the plasma whereas the density and potential fluctuations decrease as do the temperature fluctuations. Note that the spatial variation of the density and potential fluctuations is different and they are of a different magnitude. Under some conditions (DITE in helium) the density and potential fluctuations correlate spatially quite well indicating that the Boltzman relation is valid.

A particular source of difficulty in ascribing the edge fluctuations to a specific transport processes is the degree to which the fluctuations depart from the Boltzman relation and this is complicated by temperature fluctuations and the potential variation in the outer regions of a plasma.

Even cases such as shown in Figure 5 where the density and potential fluctuations are quite different, could well be reconciled if the

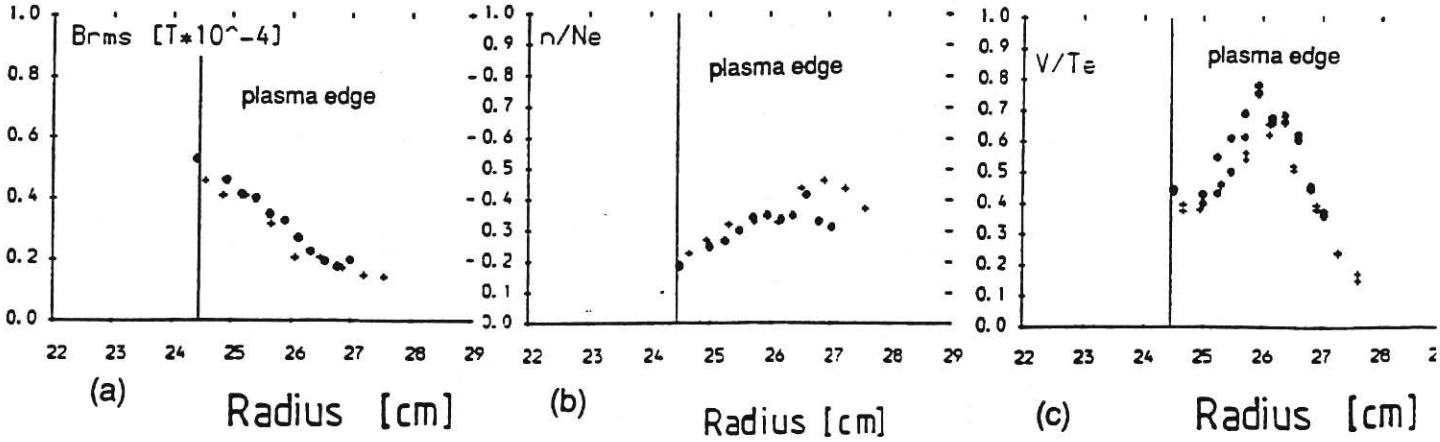


Figure 5 Radial profiles in the SOL of (a) $\tilde{B}_r$ (b) $\tilde{n}/n$, (c) $e\tilde{\phi}/kT_e$, measured using a reciprocating probe on DITE (I_p = 100kA, B_ϕ = 1.92 T, H, $\bar{n}_e = 3.7\ 10^{19}\ m^{-3}$).

temperature fluctuations and the spatial variation in plasma potential is taken into account. Caution needs to be exercised before putting too much weight on the departure from the Boltzman relation. Very similar variations in the edge fluctuations are obtained in the TEXT device as shown in Figure 6. Measurement of the temperature fluctuations seems to suggest that they are about 50% of the density fluctuations in the larger tokamaks and that there is a significant correlation between the density and potential and the temperature and potential.

The flux of particles expected theoretically is given by

$$\Gamma_i = -D\nabla n_i + n_i v - D_T \frac{n_i \partial T_e}{T_e \partial r} \qquad \text{Eq (1)}$$

where Γ is the particle flux, D the diffusion coefficient, v the radial flow velocity and D_T the thermal transport coefficient. Additional terms could also arise in the matrix associated with the ion temperature gradient and also gradient of flow velocity. The flux is normally measured by measuring the source and comparing it with the change in particle density within a given volume. The fluctuation driven particle fluxes are given by

$$-\Gamma_i = < \tilde{n}_i \tilde{E}_\theta > /B_\phi - \frac{<\tilde{j}_{\|} \tilde{b}_r>}{eB_\phi} \qquad \text{Eq (2)}$$

the principle term being the correlation between density and electric field fluctuations. The energy flux is given by

$$\begin{aligned} Q_i = \frac{3n}{2}\frac{< \tilde{E}_\theta \tilde{T}_i >}{B_\phi} + \frac{3T_i}{2}\frac{< \tilde{E}_\theta \tilde{n}_i >}{B_\phi} \\ - \underbrace{\delta_\perp . \frac{\tilde{b}_r}{B_\phi} . V_{the} n_e \frac{\partial T_e}{\partial r}}_{\text{`strong turbulence collisionless limit'}} \text{ (electrons only)} \end{aligned} \qquad \text{Eq (3)}$$

which includes the density/electric field correlation and the correlation of temperature and electric field fluctuations together with a term associated with the magnetic fluctuations, which is indicated in the strong turbulence collisionless limit. Using these expressions it is possible to compare the fluctuation driven fluxes with those directly measured from the source and changing particle or energy content. An example is shown in Figure 7 for the TOSCA device. The flux derived from the density and electric field correlation is uninfluenced by the presence

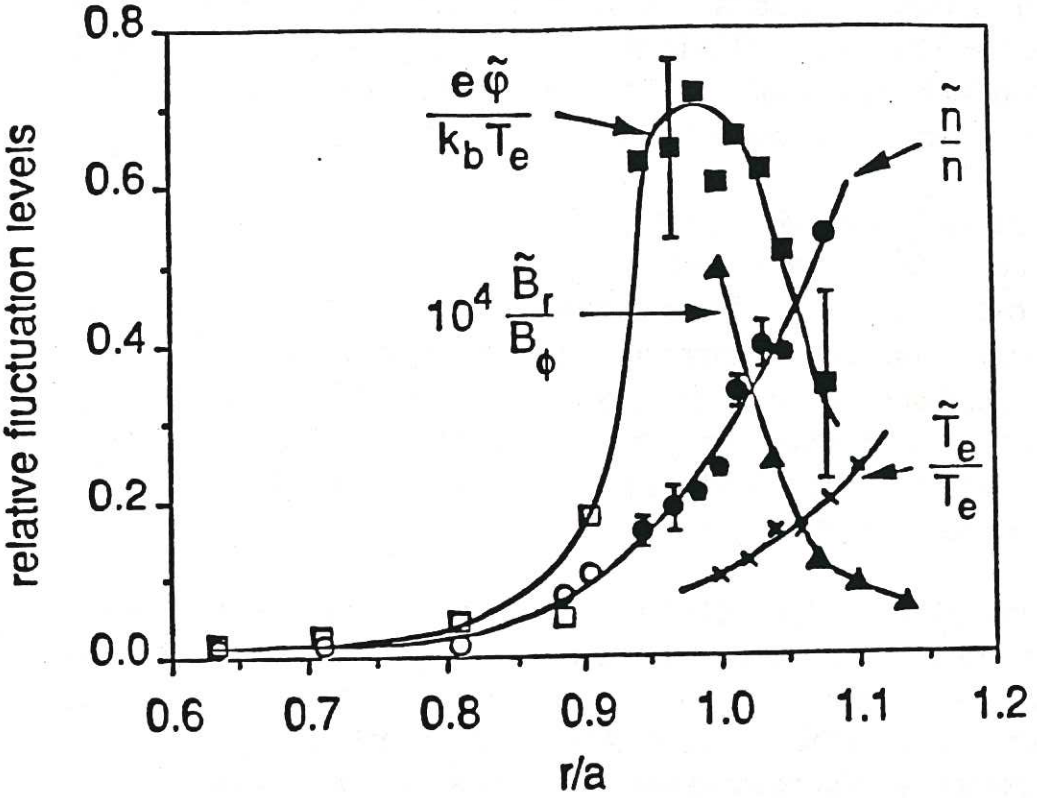


Figure 6 The spatial profiles near the limiter of $\tilde{n}/n$, $\tilde{\phi}/(k_bT_e)$, $\tilde{T}_e/T_e$ and $\tilde{B}_r/B_\phi$ measured with probes in TEXT (B_ϕ = 2T, I_p = 200 kA, $n_e = 3 \times 10^{19} m^{-3}$, H+).

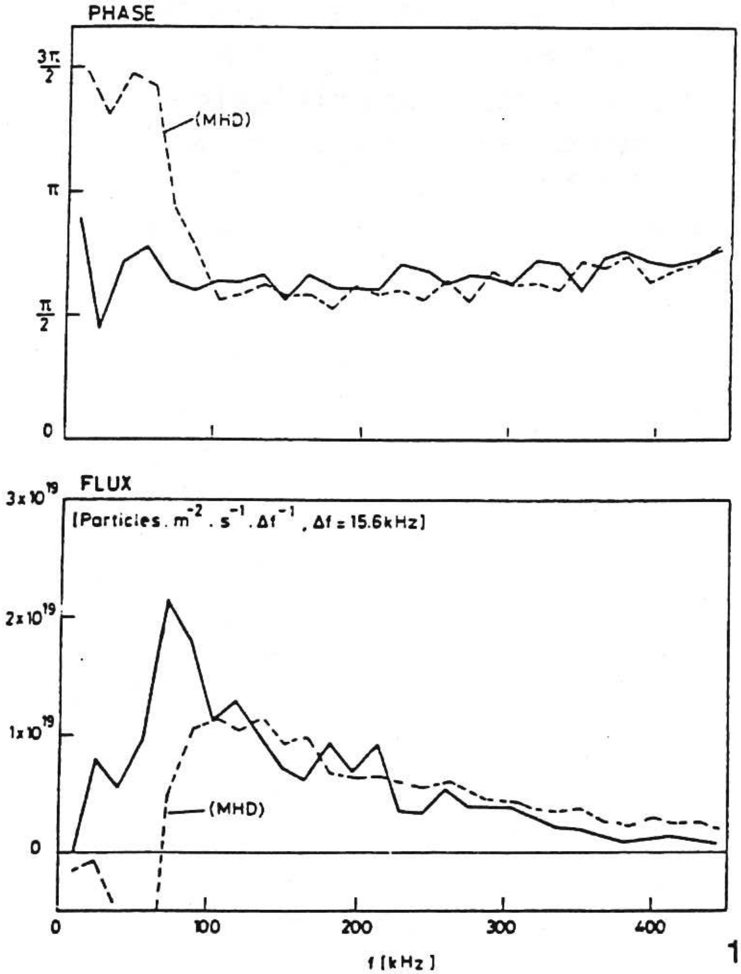


Figure 7 The effect of strong mode activity (shown by the dotted line) on flux and phase estimates on TOSCA.

of MHD activity provided the frequency is higher than that characterised by the MHD behaviour. This total flux in the absence of MHD activity is found to be in reasonable agreement with the particle confinement time as deduced from Hα measurements.

More detailed comparisons of the particle flux and its spatial behaviour have been made on the TEXT device where measurements with probes of the cross correlation coefficients together with those from the heavy ion beam probe have been compared with the flux deduced from Hα.
As Figure 8 shows there is good correspondence. We can thus tentatively conclude that the electrostatic fluctuations in the outer regions do seem to account for the observed particle flux, though the origin of these fluctuations is as yet unclear.

With the onset of additional heating, there is degradation in the particle confinement time as shown in Figure 9 for the DITE device in which the density dependence of both ohmically and additionally heated plasmas is shown. However the particle fluctuation equivalent flow only approximately balances that associated with the flow arriving at the limiter and there seems to be a discrepancy between the increase in particle confinement time as deduced by the limiter and that as deduced by the fluctuations. The outer regions show degradation of the particle confinement time as the density approaches the density limit, a phenomenon which has been suspected for some time as the density limit is approached and is not necessarily simply radiative detachment from the limiter or boundaries of the device. The fluctuation driven particle flux is increased by additional heating in numerous devices where this has been checked and the particle confinement time reduced, however there is an interesting exception to this situation and that is associated with lower hybrid current drive. This is shown in Figure 10 for the DITE device where both the magnetic fluctuation and potential fluctuation level decrease on the application of lower hybrid current drive at a power level comparable to the ohmic input power, whereas electron cyclotron heating increases the magnetic and potential fluctuations to a level above the ohmic heating level. A similar observation was made on the T7 tokamak where both lower hybrid and electron cyclotron heating were conducted simultaneously. These observations seem to suggest that the particle distribution function whether distorted in the perpendicular direction or extended in the parallel direction has an important bearing on the degree to which fluctuations drive particles and heat across the field lines.

Turning now to the more difficult problem of the energy flux driven by the fluctuations: in general the combination of density and potential fluctuations together with temperature and potential fluctuations can account for a substantial fraction of the total energy loss. The scaling however is somewhat unclear, for example Figure 11 shows recent results

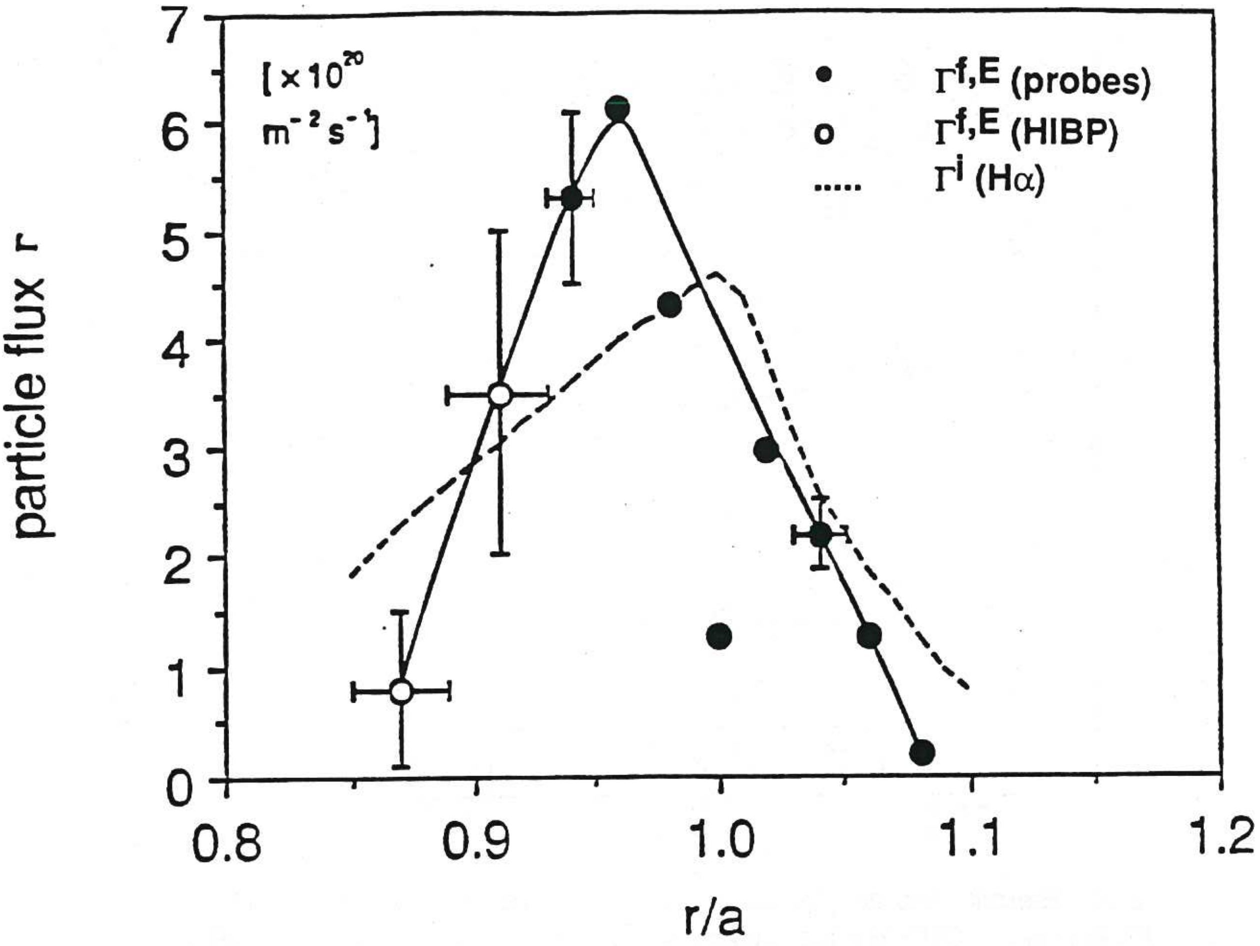


Figure 8 A comparison of working particle fluxes in TEXT ($B_\phi = 2T$, $I_p = 200$ kA, $n_e = 3 \times 10^{19} m^{-3}$, H+), the total Γ^i (from Hα) and $\Gamma^{f,E}$ driven by electrostatic turbulence. $\Gamma^{f,E}$ is measured with Langmuir probes (solid line, solid points) and the HIBP (open points).

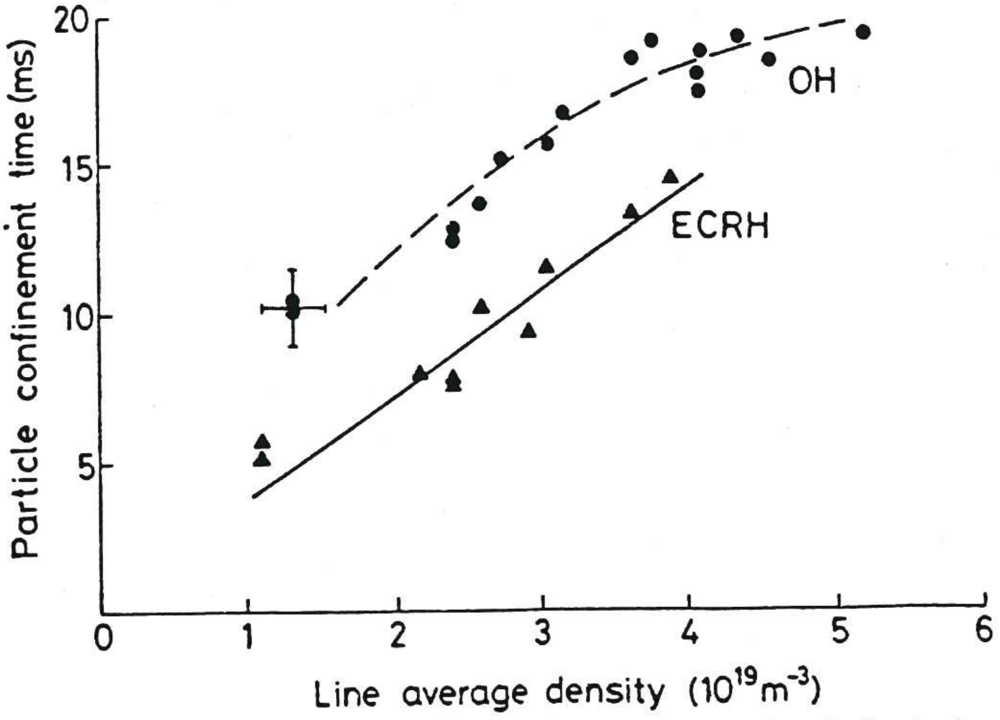


Figure 9 Scaling of the particle confinement time with density in ohmic and ECR heated discharges (I_p = 100kA, B_ϕ = 2.1 T, He, P_{ECRH} ~ 100kW).

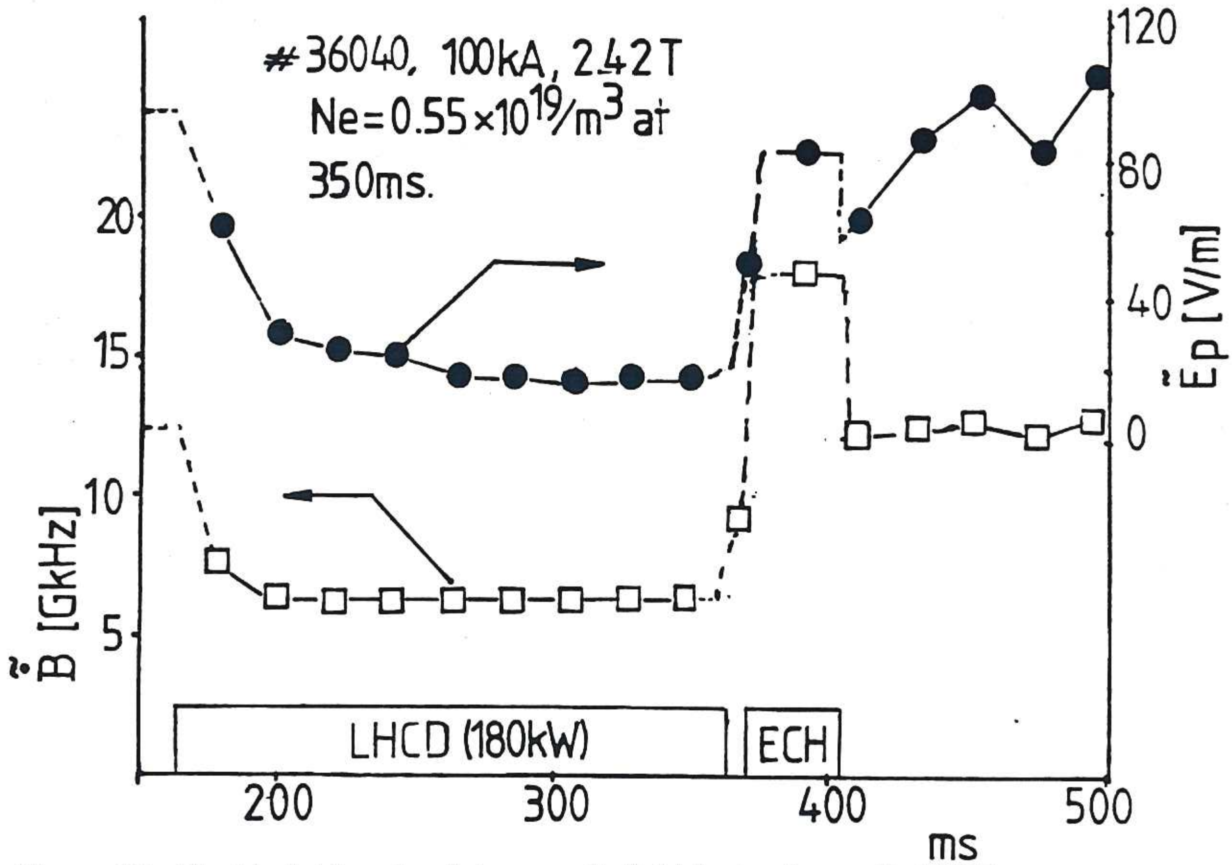


Figure 10 Electric field and radial magnetic field fluctuations with LHCD and ECRH on the DITE device, measured 2.5cm outside the last closed flux surface.

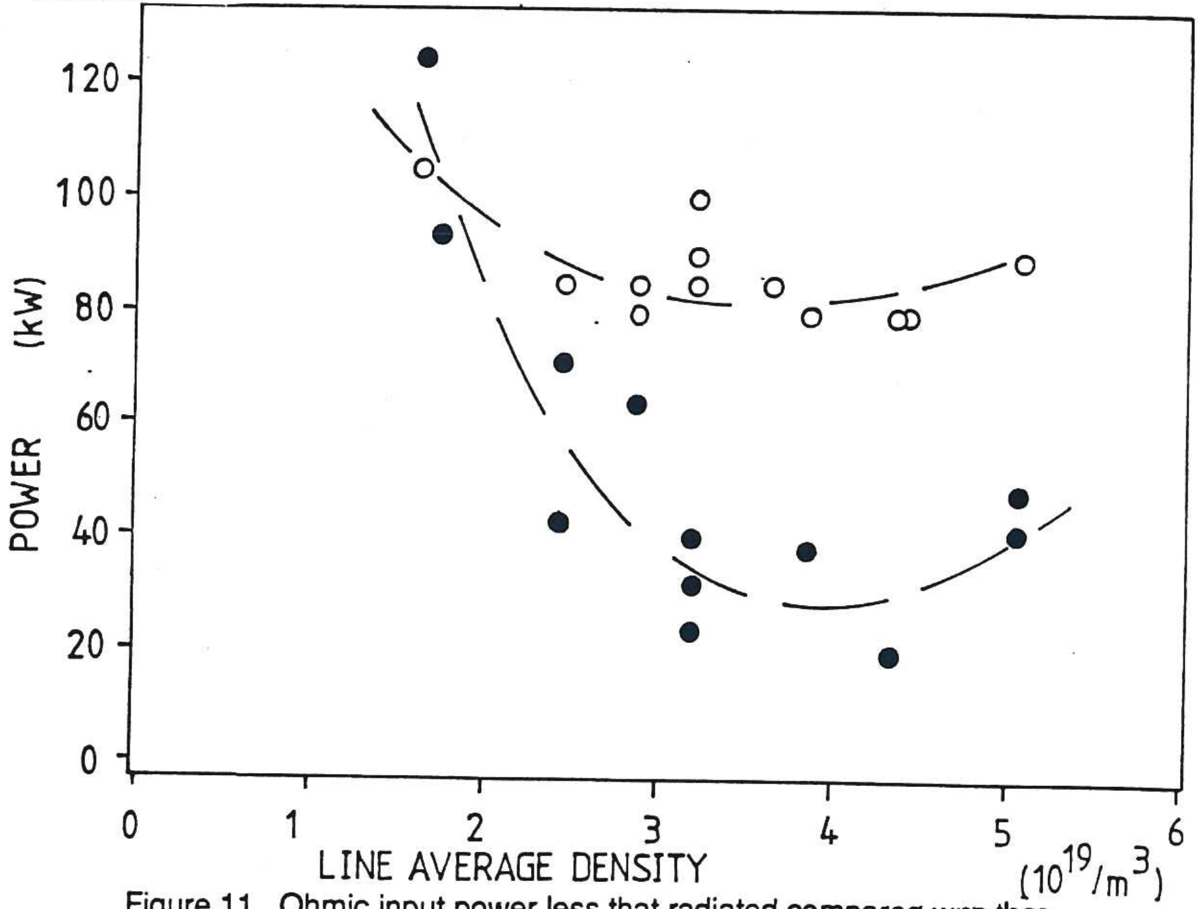


Figure 11 Ohmic input power less that radiated compared with that convected (•) and conducted (Δ) by the fluctuations as a function of density (I_p = 80kA, B_ϕ = 1.55 T, He).

from the DITE tokamak as a function of plasma density for the power convected by the fluctuations as compared with the total power loss after subtracting that which is radiated. It is clear that at low densities all the power can be accounted for but at high densities there is a substantial discrepancy. Although part of this can be associated with temperature fluctuations it may well be necessary to invoke ion temperature fluctuations larger than electron temperature fluctuations for the full power loss to be explicable. For the TEXT device similar observations have been made with probes at the edge of the plasma and these suggest that a substantial amount of the power flow is accounted for largely by the convected fluctuations with only relatively modest contribution coming from that conducted by fluctuations. Unfortunately no such measurements have yet been made in the core of the plasma and indeed there are significant problems even at the edge of the plasma associated with asymmetries which are often seen, the lack of knowledge of the ion temperature fluctuations and the fact that sometimes quasicoherent modes are present. The asymmetry problem however should not be overstated on the DITE device the reciprocating probe uses some 5 separate measurements of the flux covering a poloidal angle of some 70 degrees without any marked asymmetry being apparent. The character of the fluctuations might point in favour of those driven by the resistivity gradient or possibly resistive ballooning modes rather than simply from drift wave turbulence. However this conclusion should be treated with caution particularly because of the lack of precise and spatially resolved temperature fluctuations at the present time.

Magnetic fluctuations

It would seem to be appropriate to comment on the high frequency magnetic activity which occurs in the same range as that observed both by edge probes and also by laser scattering. This high frequency activity has a frequency spectrum which falls off as f^{-4} both in pinches and tokamaks and whose fractional amplitude at the minimum radii which can be explored with probes in tokamaks is ~ 10^{-4} compared with 10^{-2} in pinches. The amplitude may (DITE and TCA) or may not (TEXT and TOSCA) decrease with density and on all devices where measured, it increases towards the centre of the plasma. Figure 12 shows the magnetic fluctuation behaviour with increasing density for ohmically heated and electron cyclotron resonant heated discharges in the range from 40 - 250 kHz just behind the limiter on DITE. This activity is found to be quite uncorrelated with the low mode number activity, when present. The spatial variation can be obtained with reciprocating probes and has also been obtained up to half radius on the CLEO device.

The amplitude increases with additional heating but decreases with lower hybrid current drive. It is well correlated both on DIII-D and JET with the transition from L to H modes. The fluctuations, like density and potential fluctuations, are found to be strongly two dimensional with very long correlation along field lines. It is found that the fluctuations are closely linked to the density fluctuations in tokamaks, stellarators and pinches through the pressure balance relation $\tilde{b}_{||}/B = \beta/2.\tilde{n}/n$. This is verified by spatial and temporal measurements.

It should be pointed that there are difficulties with edge magnetic fluctuations in that they are found to be very sensitive to localised phenomena, eg gas puffing, even though there is no global change in either mean average density or energy confinement time. Detailed measurements of the propagation direction and behaviour close to the limiter region indicate that they arise from distributed current sources relatively close to the point of measurement.

It would seem from these observations that since the magnetic field fluctuations often have the wrong dependence on different plasma parameters, that they have the wrong spatial dependence compared with the thermal and particle diffusivities, that the amplitude measured in the outer regions of tokamaks seems to be too small using current estimates for the thermal diffusivity for given fluctuation levels, that they are unlikely to explain or make a significant contribution to anomalous transport in the outer regions of the tokamak. However the situation is somewhat different at high beta, as is also the case in pinches, since then the fluctuation level increases and may well become large enough to become significant. Perhaps the most important question associated with magnetic relative to electrostatic activity is how its amplitude behaves in the core of a plasma and how this correlates with the confinement. All that one can say at present is that, using the measured density fluctuations and pressure balance relation or alternatively using results from strong fluid turbulence theory ie equipartition of energy between the fluid and magnetic motions, and deducing the fluid motion from the potential spectrum and wave numbers in the core of the plasma, that fractional fluctuation levels, $\tilde{b}/B \sim 10^{-4}$ are present which could provide a significant contribution to anomalous transport.

Sawtooth and heat pulse propagation

A wide range of experiments have demonstrated the excitation of internal microturbulence close to the q=1 surface associated with the sawtooth crash. A more controlled technique of looking at the internal fluctuation level excited by the propagation of a thermal wave is obtained by using localised modulated electron cyclotron resonant heating. Measurements of this sort have been conducted on the DITE tokamak and these show clear evidence for the diffusive delay in the excitation of edge fluctuations, eg

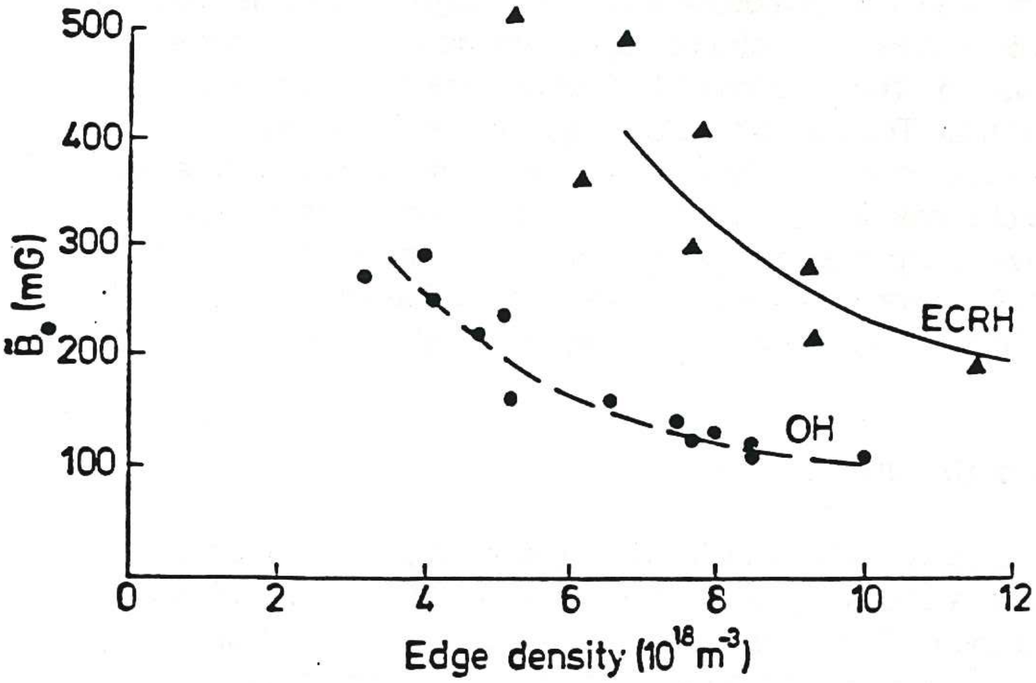
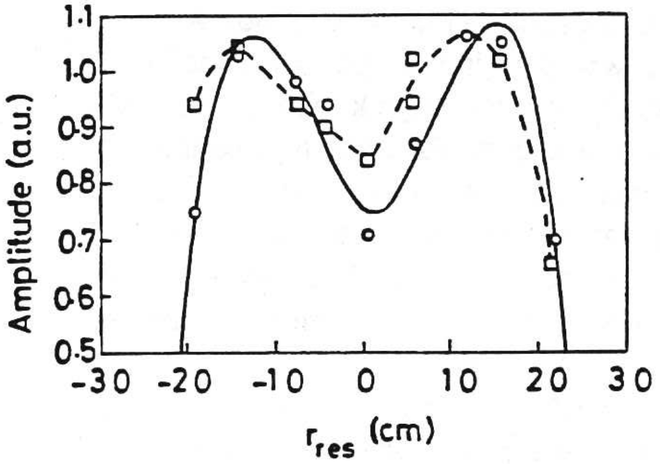


Figure 12 Poloidal field fluctuations in the frequency range 40 to 250 kHz measured 10mm behind the limiter radius as a function of density in ohmic and ECR heated discharges (I_p = 100kA, B_ϕ = 2.1 T, He, P_{ECRH} ~ 100kW).

Modulation amplitude vs resonance position



Phase delay vs resonance position

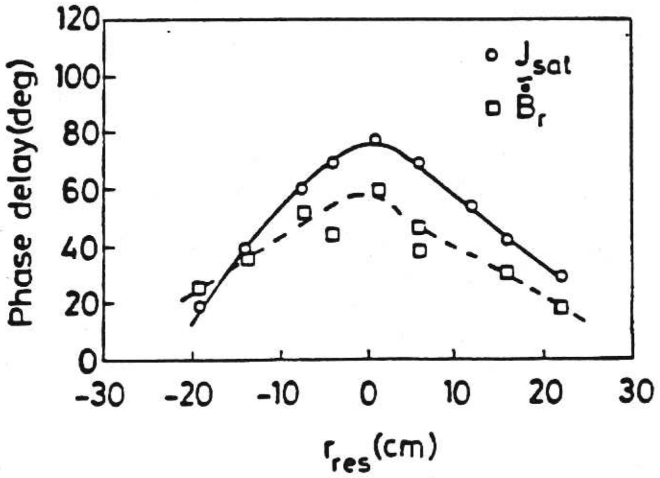


Figure 13 Amplitude and phase of the ion saturation current and radial field fluctuations as a function of ECRH resonance position for second harmonic heating on the DITE device.

Figure 13 shows the amplitude variation of the edge fluctuations and mean saturation current as the electron cyclotron resonance position in the plasma is varied. The variation of the fluctuation of the mean saturation current is similar. The electron cyclotron emission measurements as well as X-ray measurements for the thermal wave phase delay time agree well with those observed for the fluctuations, which would seem to suggest that diffusive transport at least controls these plasmas in which only a small modulated additional heating pulse is applied to an ohmically heated plasma. There is no evidence for any form of radiative transport in such discharges.

Structure of the turbulence

There was a considerable amount of early work on pinches where the spectrum, correlation lengths, microscales, delayed spatial correlations, triple correlations etc were measured [9]. Unfortunately very little work on the real structure of the turbulence in tokamaks, pinches and stellarators in recent years has been carried out. However some interesting work which bears upon this problem of drift wave turbulence and its possible coupling to flute instabilities has been conducted on the UMIST quadrupole [10].

The cascade of energy and flow direction is an important question, for example in 2D turbulence, instead of a cascade from low to high wave numbers, it is expected that the flow would be in the opposite direction. In the quadrupole[10] such a flow of energy from high k to low k has been deduced. Measurements of skewness and curtosis of the turbulence are particularly important but so far no measurements have been reported. Self organisation phenomenon such as clumps and holes may well be important and again more work is required. There has been some work on the bispectrum and trispectrum measurements in the tokamak but so far no really important conclusions have been drawn from this work. Conditional sampling is a technique which could well be of value in elucidating some of the transport phenomena. Dimensionality has been tried by a number of groups but apart from clear results obtained in MHD dominated regimes there are no clear results which have assisted in understanding the basic nature of the anomalous transport process at the edge of the plasma.

It is very important to note that the lower hybrid current drive plasmas which display markedly non-Maxwellian distribution functions produce very different particle confinement and fluctuation behaviour and the correlation between this and anomalous transport yet remains to be explored. Temperature fluctuations have to be more carefully characterised in terms of moments of the distribution function which are particularly sensitive to non-Maxwellian behaviour.

Radiative energy transfer is an area to be explored further and is clearly apparent in the MHD spectra of noncircular tight aspect ratio devices. The higher harmonic behaviour of this magnetic activity would be expected to couple to the electrostatic behaviour suggesting some contribution to transport from this process.

Conclusions

Strong electrostatic turbulence in the outer regions would seem to be responsible for the particle fluxes and a major part of the energy flux in both tokamaks and stellarators, both in ohmically and additionally heated discharges. However the origin of this turbulence is at present unknown.

The measurements of magnetic fluctuations at the edge appear on present theories to be too small to contribute significantly to the thermal loss though with additional heating as the plasma pressure rises, the fluctuations increase correlated with a reduction in confinement and they may have some bearing on anomalous processes particularly in the hot core of the plasma.

Unfortunately very little is known about the fluxes driven by the fluctuations in the hot central core nor about the detailed structure or origin of the turbulence in the outer regions.

Small tokamaks as well as large tokamaks and alternate confinement systems together with solar astrophysical and magnetospheric phenomena all have an important role to play in the understanding of anomalous transport and strong plasma turbulence. There is a need for new diagnostics and techniques to study the turbulence in the hot core of confined plasmas.

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