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FUSION RESEARCH CENTER

Final Performance Report

A Portable and Independent Edge Fluctuation Diagnostic

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Project Overview

1.1 Past. A compact self contained portable probe system has been designed and developed to diagnose the edge plasma of devices of different sizes and configurations. The system measures both the mean and the fluctuation quantities of density, temperature and potential from a standardized Langmuir probe array using a fast reciprocating probe drive. It can also be used for other fluctuation diagnostics, such as magnetic probes. The data acquisition and analysis is performed on a Macintosh IIfx which provides a user-friendly environment. The results obtained by the signal processing routines are stored in a tabloid format to allow comparative studies. The resulting database is a core part of the portable signal analysis system.

1.2 Current. To date measurements have been performed on the stellarator ATF, the reversed field pinch ZT40(M), and the tokamaks TEXT, Versator, Phaedrus-T and TFTR. The data are presently being analyzed and the results collected into the database for the purpose of edge turbulence and transport studies. Existing published data are also being included. Collaboration has also involved (as well as the experimental groups listed above) the UCSD theory group and the ORNL computational group. The project has stimulated fruitful collaboration and exchange of expertise among the above listed groups. The edge database, an output of this project, will provide readily available information for other experimental groups to compare their results with, and for theoretical groups to validate (or otherwise) the predictions of their models.

2. Project Output.

Here we present a summary of the work emanating from our data base. Characteristics of electrostatic and magnetic turbulence in the edge of tokamaks, stellarators and reversed field pinches have been compared and contrasted. Scalings of turbulent fluctuation levels and wave numbers are discussed. Electrostatic turbulence is shown to explain edge density scale lengths in all three device types. Electrostatic fluctuations also determine edge thermal transport in tokamaks and stellarators, while magnetic fluctuations explain edge thermal transport in reversed field pinches and runaway electron transport in tokamaks and stellarators.

The object is to compare and contrast turbulence characteristics in the edge of tokamaks, stellarators (including torsatrons) and reversed field pinches (RFP's). The main differences between the machines, typified by comparing TEXT, ATF and ZT40, are

shown in *Table 1* and *Table 2*. Properties which might be expected to influence instabilities and turbulence include local gradients, dimensionless parameters, magnetic geometry factors such as magnetic shear and curvature, and limiter configurations. Note the different values of safety factor q , and the lack of plasma current I_p in the electron cyclotron resonance heated (ECRH) torsatron ATF. In all three devices the known edge gradients are similar, except for those associated with I_p (there need be no net I_p in a stellarator, and even locally any currents can be extremely small). The density is somewhat higher in ZT40. Concerning dimensionless parameters, β is much higher and q much lower in the RFP.

An important comparison is between ATF and TEXT; any differences in turbulence between these might be attributed to plasma current, alternatively if the turbulence is identical then plasma current is not important. Differences in turbulence between all three devices will be much harder to interpret, because the RFP has many distinguishing features. If the turbulence looks similar between the three devices, and if a common mechanism is sort, then either the local gradients (except those associated with I_p), or the boundary conditions associated with the limiter, might be responsible. However, at least differences associated with different values of q and β are to be expected.

Table 1. Magnetic Geometry

<u>Parameter</u>	<u>Tokamak</u>	<u>Stellarator</u>	<u>RFP</u>
Average curvature	Good for $q > 1$	Good or Bad	Bad
Local curvature	Good & Bad	Good & Bad	Bad
Magnetic shear s	Medium ($L_s \approx R$)	Medium to 0	High ($L \approx a$)
	$dq/dr > 0$	Usually $dq/dr < 0$	$dq/dr < 0$
Trapped particles	High, $\approx \sqrt{(2\epsilon)}$	High or Low	Low

Table 2. Characteristic Edge Turbulence Parameters at $r \approx a$

<u>Parameter</u>	<u>TEXT</u>	<u>ATF</u>	<u>ZT40</u>
R (m)	1.0	2.1	1.14
a (m)	0.26	0.27	0.20
I_p (kA)	250	0 (ECRH)	120
B (T)	2	1	0.13
q(a)	3.3	1	0.02
$T_e(a)$ (eV)	30	25	25
$n_e(a)/10^{18}$ (m ⁻³)	2	1	10
L_n (cm)	3	4	2
L_{Te} (cm)	4	4	8
$\tilde{n}/n$	0.1-0.2	0.05-0.1	0.3-0.5
$\tilde{\phi}/T_e$	0.15-0.3	0.1-0.2	0.4-0.6
$\tilde{T}_e/T_e$	0.05-0.1	0.1	0.2-0.5
$\tilde{b}/B(a)$	10^{-5}	10^{-6}	0.01-0.02
$\sigma_{k\perp}$ (cm ⁻¹)	3	1	0.1

significantly different parameters are in **bold** type. σ_k is the width of the k spectrum.

SPECIFIC TURBULENCE CHARACTERISTICS

MHD Activity

It is important to distinguish "low frequency Magneto Hydro Dynamic (MHD)" activity from the "high frequency (i.e. small scale)" turbulence we wish to study and compare. The association between frequency f and inverse scale size is made because $f \propto k$, the wave number. The RFP is very different from the other two devices because of the close packed major rational surfaces within the reversal layer. Non linear global tearing modes with $m = 1$, $n \approx 2R/a$ exist, which result in an MHD dynamo and the generation of part of the equilibrium currents and fields. To the extent that magnetic field lines are frozen into the plasma, any magnetic fluctuations are accompanied by a radial density convection. If this is the case then we should not expect to find large similarities between RFP, tokamak and stellarator density fluctuation data.

To investigate small scale fluctuations for grossly stable tokamaks and stellarators $\tilde{n}$ can be used regardless of frequency range, but frequency filtering should be applied to magnetic data. The typical data presented here include $10 \text{ kHz} < f < 500 \text{ kHz}$. To

investigate small scale magnetic turbulence in RFP's the magnetic fluctuations must be filtered to separate the effects of the low frequency internally resonant tearing modes. Filtering must also be applied to the electrostatic fluctuations if the effects of the radial convection associated with these internal global modes are not to be counted. The data here typically include $f > 50$ kHz. However, this means of separation is very approximate, so that distinguishing small scale turbulence effects is subject to large uncertainties.

Fluctuation Level Scalings, and the Effects of Perturbations

If the density gradient drives the turbulence and the drive stops when the density scale length $L_n \rightarrow \infty$ then $\tilde{n}_{rms}/n \approx (k_{r,rms}L_n)^{-1}$. For Gaussian isotropic turbulence we expect $\tilde{n}_{rms}/n \approx (\bar{k}L_n)^{-1}$, with $\bar{k}$ an average power weighted wave number. Results of this comparison are shown in *Figure 2.2.1*. The box represents the limits of data taken in the TEXT scrape off layer (SOL). The straight line is the relationship $\tilde{n}_{rms}/n = (\bar{k}L_n)^{-1}$. Also shown are data presented by C. Surko. Stars (*) denote data for interior fluctuation levels.

The following conclusions are drawn:

- a) The relationship $(\tilde{n}/n)_{rms} \approx 1/(\bar{k}L_n)$ is found, with ZT40 data being farthest from the general trend. Data from Tokapole show that it is L_n , not L_{Te} or L_p , which is important.
- b) Within one tokamak (TEXT) the connected diamonds shows that the full radial profile is also approximately consistent with this simple scaling.
- c) Within one tokamak (e.g. TEXT) the scaling is not strictly adhered to. Other parameters are important, e.g. impurity radiation, ionization and velocity shear, discussed later.
- d) It has been suggested that material surfaces can directly drive turbulence through the boundary conditions they impose. *Figure 2.2.2* shows a large increase in $\tilde{n}/n$ is found following limiter insertion in Tokapole. However the scaling suggests this might be a result of the inclusion of a parallel sink which reduces L_n , rather than a direct drive. ZT40 data show the same trend.
- e) Data from DIII-D (*Figure 2.2.2*) shows a scaling of $(\tilde{n}/n)_{rms}$ with $1/(\bar{k}L_n)$ during the transition from L to H mode which is orthogonal to the general trend. The same

orthogonal trend is found during the L to H transition (biased probe) in CCT. These results, obtained outside the shear layer (discussed later) suggest a drive other than L_n .

f) The similarity in tokamak and stellarator data suggest a common cause, which is not due to plasma current.

g) Magnetic fluctuations are accompanied by a radial density convection n_c . This is only significant in the RFP, where $\tilde{n}_c/n \approx r\tilde{b}_r/(B_\theta L_n)$. This convection leads to no net particle flux. Data obtained with and without limiters in ZT40 are plotted in *Figure 2.2.2*. The arrow indicates the trend with limiter insertion; $(\tilde{n}/n)_{rms}$ increases from 0.5 to 0.9 (all frequencies, labeled total), while L_n decreases from 2 cm to 0.6 cm. The measured $(\tilde{b}_r/B_\theta)_{rms} \approx 0.015$ implies a convective $(\tilde{n}_c/n)_{rms}$ of 0.15 increasing to 0.5, i.e. explaining a large part of the increase. Filtering ($f > 50$ kHz) can be used to partially remove the effects of the global modes: in this case $(\tilde{n}/n)_{rms}$ (50-300 kHz) increases from 0.3 to 0.56 (labeled HF in *Figure 2.2.2*).

Figure 2.2.1. The dependence of density fluctuation level $(\tilde{n}/n)_{rms}$ on $(\bar{k}L_n)^{-1}$ for various machines. The box represents SOL data, and the diamonds a full radial profile, in TEXT. * denotes interior data.

Figure. 2.2.2. The variation of density fluctuation level with specified perturbations applied.

Wave Number Scaling

If the turbulence is drift wave like we expect $\bar{k}_\perp \rho_s \approx 1$, with ρ_s the ion gyro radius using T_e , so $\bar{k}_\perp \propto B T_e^{-0.5}$. If the magnetic geometry is defining the structure then we might expect $k_\perp$ to be determined by the lowest (most unstable) mode around the rational surface where $q = m/n$, so that in tokamaks and stellarators $k_\theta \approx q(a)/a$. Here m is the poloidal and n the toroidal mode number. *Figure 2.3.1* shows that between machines $\bar{k}_\perp \propto B$, with TFTR an exception. *Figure 2.3.2* shows limited data where $\bar{k}_\perp \rho_s \approx 0.05$ to 0.1 (except in TFTR); i.e. the wavelengths are > 10 times longer than expected from drift wave theories. However, while $\bar{k}_\perp \rho_s \approx \text{constant}$ appears to describe the data, *Table 2* suggests that comparing tokamaks and stellarators, $\bar{k}$ is dependent on q , i.e. the magnetic geometry is also important. The small values of $\bar{k}_\perp \rho_s$ found in TFTR, still under investigation, might be caused by MHD activity which is not correctly filtered.

Figure 2.3.1. The dependence of wave number $\bar{k}_\perp$ on field B .

Figure 2.3.2. The wave number dependence $\bar{k}_\perp$ on $1/(\rho_s)$.

ELECTROSTATIC TURBULENCE DRIVEN FLUXES

Figure 3.1. A comparison of fluctuation driven flux $\Gamma_{\tilde{n}E}$ and Γ_{SOL} derived from L_n .

Figure 3.2. A comparison of D_{SOL} with D_{Bohm} .

The measured turbulence produces a particle flux $\Gamma_{\tilde{n}E}$. We can also derive an effective particle flux $\Gamma_{SOL} = 0.5nc_s L_n / L_c$ from the SOL equilibrium parameters (c_s is the sound speed, L_c the parallel connection length), and compare it with $\Gamma_{\tilde{n}E}$. Figure 3.1.1 shows both, derived simultaneously at the same location. The excellent agreement is fortuitous, because of the simplicity of the model. Nevertheless, the data show that locally Γ_{SOL} represents $\Gamma_{\tilde{n}E}$ fairly accurately, and that electrostatic turbulence is important in determining total fluxes. In the RFP the convective density fluctuations, associated with the tearing modes, do not contribute to the fluctuation driven flux.

We can now use published values of L_n to investigate scaling of transport related parameters. As an example Figure 3.2 shows a comparison of $D_{SOL} = -\Gamma_{SOL} L_n / n$ with the Bohm value D_{Bohm} . Many effects such as ionization are not accounted for in the derivation. Data first collected by McCracken and Stangeby is included, designated by "S-M". Often, within one machine, the trend is one of increasing D_{SOL} with increasing T_e . Taking a constant times D_{Bohm} to represent edge particle transport is not a good idea

ASYMMETRIES AND CONVECTIVE CELLS

Most fluctuation measurements are made at very few positions, so that symmetry must be invoked in order to calculate total values of, e.g., fluctuation driven fluxes. In the

SOL of TEXT poloidally symmetric equilibrium and fluctuation quantities were found over $\pm 20^\circ$ ($\pm 10\text{cm}$) about the top. However, data from TF-1 and CCT clearly show poloidal asymmetries in both equilibrium and fluctuating parameters in the SOL and inside the main plasma. It is not clear if these asymmetries and resulting dominant DC convection in the main plasma are universal. Have experimentalist missed their existence, because of insufficient resolution? Is their presence dependent on particular parameters? Could it be a diagnostic problem?

THE SHEAR LAYER

Figure 5.1 shows the phase velocity (v_{ph}) profiles near the plasma edge from four machines: TEXT (ohmic heated (OH) tokamak with average magnetic shear s), ASDEX (OH tokamak with separatrix and high s , ATF (ECRH torsatron with average s) and W7AS (ECRH stellarator with very low s). The ordinate is the distance from the inversion point of v_{ph} , the "shear layer". All machines except some small tokamaks, e.g. Tokapole, and perhaps RFP's, exhibit this phenomena. Velocities as high as 10^4 ms^{-1} are reported on W7AS. Many possible production mechanisms have been proposed. It is found with various limiter configurations: for example an upper rail or outer rail limiter (TEXT), and an inner toroidal belt limiter (TFTR).

Figure 5.1. Phase velocity profiles; the ordinate

Figure 5.2. Profiles of autocorrelation

is the distance from the inversion point (velocity shear maximum).

time in the shear layer of TEXT and ASDEX.

Where $|\partial v_{ph}/\partial r|$ ($\approx (1/B)\partial E_r/\partial r$) is high any turbulent structures experience a differential mass velocity across a radial correlation length, which will suppress the turbulence. Such a mechanism explains the measured decrease in auto-correlation times in TEXT, shown in *Figure 5.2*, and may explain the H mode. However, results from ASDEX do not show a clear suppression, although it is possible that data sufficiently far into the main plasma have not been obtained yet.

TEST PARTICLE TRANSPORT

One way to quantify the role of turbulence is to derive and compare test particle diffusivities. A quasi linear calculation using a decorrelation time $2\pi R/v_{||}$ leads to

$$D = \pi R \left[\frac{1}{v_{||}} \left(\frac{\tilde{E}_{\perp}}{B} \right)^2 + v_{||} \left(\frac{\tilde{b}_{\perp}}{B} \right)^2 + 2 \left(\frac{\tilde{b}_{\perp}}{B} \right) \left(\frac{\tilde{E}_{\perp}}{B} \right) \cos \alpha \right] \quad (1)$$

with $\cos(\alpha)$ describing the phase and correlation between $\tilde{b}_{\perp}$ and $\tilde{E}_{\perp}$, assumed $\pi/2$. No allowance is made here for the effects of orbit averaging, expected only at higher energies than those considered or if the particles have perpendicular energy. The first term is a random walk with $\mathbf{E} \times \mathbf{B}$ drifts (electrostatic), the second a random walk along perturbed field lines (magnetic), and the third accounts for any correlation between the electrostatic and magnetic terms. It is usual to associate the calculated test particle diffusivity with the electron thermal diffusivity χ_e and the runaway electron particle diffusivity D_{ra} .

D (m^2/s)

Figure 6.1. The energy dependence of D , with an experimental $D_{runaway}$ and χ_e in the edge of TEXT. Solid line is total, broken line is electrostatic component, dotted line is magnetic component.

D (m^2/s)

Figure 6.2. The energy dependence of D in an RFP. Solid line is total, broken line is electrostatic component, dotted line is magnetic component

Figure 6.1 (solid line) shows the expected dependence of D on energy E for data relevant to the edge plasma of TEXT ($(\tilde{b}_\perp/B_\phi)_{\text{rms}} \approx 3 \times 10^{-5}$, $\tilde{E}_{\text{rms}} \approx 30 \text{ Vcm}^{-1}$); the values typify most tokamaks and stellarators. As the energy increases the dominating process changes from $\mathbf{E} \times \mathbf{B}$ drifts to magnetic fluctuations, and the energy dependence changes from $1/\sqrt{E}$ to $\sqrt{E}$. The measured edge $\chi_e \approx 8 \text{ m}^2\text{s}^{-1}$ at $T_e \approx 80 \text{ eV}$ is explained by electrostatic turbulence, while the measured edge $D_{\text{ra}} \approx 1 \text{ m}^2\text{s}^{-1}$ at $E \approx 1 \text{ MeV}$ is dominated by the magnetic turbulence. *Figure 6.2* (note the different scale) shows that in RFP's the very large magnetic fluctuations ($(\tilde{b}_\perp/B_\theta)_{\text{rms}} \approx 0.01$, $\tilde{E}_{\text{rms}} \approx 2 \text{ Vcm}^{-1}$) always dominate the diffusivity, and lead to very large test particle transport and short confinement times. In fact measurements show the edge of RFP's contain electrons which have apparently reached the edge from the core without losing energy. Magnetic turbulence dominates edge energy transport in RFP's.

SUMMARY AND CONCLUSIONS

First we consider tokamak and stellarator edge regions. We find a remarkable similarity in the characteristics of the turbulence, which suggests that plasma current is not an important driving term. Comparing TEXT and ATF there is a somewhat different value of the wave number k , which might represent a scaling with safety factor or $1/\rho_s$; in either case k increases with field B . Comparing different machines shows the normalized fluctuating density scales approximately inversely with the density scale length L_n , suggesting L_n is one of a number of driving terms. Limiters affect the turbulence, but it is not clear if they drive it directly. A velocity shear layer exists, in which there is some evidence for turbulence suppression. In both machines electrostatic turbulence generally plays an important role in determining edge particle fluxes. However asymmetries and convective cells have been found, bringing into question the general statement that "electrostatic turbulence explains edge particle fluxes". Bohm scaling is not useful for describing the effective diffusivities. Concerning magnetic fluctuations, they are not usually important in determining electron thermal transport, but do explain runaway electron confinement.

Complications appear in trying to include the RFP in the comparison, because of the dominant global MHD modes and their influence. It is difficult to separate their effects accurately, so that is difficult to assess their contribution to the fluctuation characteristics.

It is clear that electrostatic turbulence can explain particle transport in the RFP, but the large magnetic fluctuations dominate energy transport. The fluctuating normalized density and wave number scale in a similar manner to those in the tokamak and stellarator, particularly if filtering is applied to include only the smaller scale RFP turbulence. Perhaps this indicates a common drive, again L_n (or any parameter which scales with L_n) is important. It is not clear if the RFP exhibits a velocity shear layer.

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