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Fluctuations in tokamak edge plasma

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Abstract : The fluctuations in plasma parameters *e.g.* density, potential, electric and magnetic fields, temperature etc., in the edge region of the plasma have been studied extensively, in several tokamaks, as they are widely believed to influence the confinement properties in tokamaks. The techniques used to carry out such measurements are discussed and the results of some of such studies are reviewed.

Keywords : Tokamak plasma parameters, fluctuations.

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1. Introduction

Plasma in edge region is characterised by low density ($n_e \approx 10^{12}$ - 10^{13} cm^{-3}) and low temperature ($T_e \approx 5 - 50$ eV). Fluctuations in the edge plasma regions in several tokamaks are, however, known to play inportant role in the overall confinement of the plasma as evidenced by improved global confinement in the H-mode discharges [1], TFTR super shots [2], and discharges with improved ohmic confinements in ASDEX [3,4]. It is widely believed that fine scale fluctuations in plasma parameters are responsible for the observed rates of crossfield transport of particles and energy much higher than that accounted for by the collisional effects. Unlike neoclassical transport, which depends on the mean plasma properties and the collisions, turbulent transport from fluctuations in plasma parameters.

Some of the recent experiments using highly biased probes to trigger the transition to a H-mode like regime [5-8] have further demonstrated the important role played by edge plasma fluctuations in controlling the particle/energy confinement in the core region. The subject of plasma fluctuations is a very wide one and has been exhaustively reviewed [9-11]. In this paper, it is proposed to summarise the main features of the fine scale electrostatic fluctuations in the edge region of the plasma as observed in several tokamaks. In the following, we briefly outline the techniques used to study the nature of fluctuations in various plasma parameters and to obtain crossfield transport. The observed features of the fluctuations is then summarised. Fluctuation induced transport is discussed in subsequent section.

2. Fluctuations and crossfield transport

Crossfield transport of the particles and the energy, in the edge region of the tokamak, occurs at much faster rates as compared to the collisional transport and the fine scale fluctuations are widely believed to be responsible for such anomalous transport [9, 12-15]. The fluctuating poloidal electric field, $\tilde{E}_\theta$, for example, causes a fluctuation radial drift, $\tilde{E}_\theta \times B_T$ which along with fluctuating density, $\tilde{n}_e$, may result in a net averaged radial particle outflow due to electrostatic (ES) fluctuations

$$\Gamma_\perp^{ES} = < \tilde{n}_e \left(\frac{\tilde{E}_\theta}{B_T} \right) > \tag{1}$$

provided the phase difference between $\tilde{E}_\theta$ and $\tilde{n}_e$ is different than 90°. Similarly a net electromagnetic (EM) fluctuation flux can occur due to fluctuating radial magnetic field, $\tilde{B}_r$, and the parallel velocity, $\vartheta_\parallel$, in the scarp off layer (SOL);

$$\Gamma_\perp^{EM} = < \tilde{n}_e, \vartheta_\parallel \left(\frac{\tilde{B}_r}{B_T} \right) > \tag{2}$$

A part of the flux parallel to the magnetic field, is diverted to the radial direction due to fluctuating component of the magnetic field.

Four contributions to the crossfield energy flux density, Q, can also be written down as follows:

$$Q_{conv}^{Es} = \frac{5}{2} kT_e \Gamma_\perp^{ES} \tag{3}$$

$$Q_{conv}^{EM} = \frac{5}{2} kT_e \Gamma_\perp^{EM} \tag{4}$$

$$Q_{cond}^{ES} = \frac{5}{2} n_e < k\tilde{T}_e \frac{\tilde{E}_\theta}{B_T} > \tag{5}$$

$$Q_{cond}^{EM} = -\frac{5}{2} \tilde{n}_e \chi_e (\tilde{B}_r) \frac{dT_e}{dr} \tag{6}$$

where $\chi_e(\tilde{B}_r)$ is a model dependent function [10].

These fluxes can be used to calculate the associated diffusion coefficients and heat conductivities. The experimental evaluation of these coefficients, requires measurements of large quantity of data. For example the particle flux density due to electrostatic fluctuations, expressed as

$$\Gamma_{\perp}^{ES} = \frac{}{B_T} \int \tilde{n}_{rms}(\omega)\tilde{\phi}_{rms}(\omega)\bar{k}_{\theta}(\omega)\gamma(\omega)\sin(\alpha(\omega))d\omega \qquad (7)$$

requires the estimates of $\tilde{n}_{rms}$ and ϕ_{rms} the amplitude obtained from auto-power spectra of $\tilde{n}_C$ and $\tilde{\phi}_p$ respectively, the poloidal wave number $\bar{k}_{\theta}(\omega)$ at frequency ω, the phase angle $\alpha(\omega)$, and the mutual coherence $\gamma(\omega)$, between $\tilde{n}_e$ and $\tilde{\phi}_p$.

3. Experimental techniques

In edge plasma, electrostatic fluctuations are most readily measured using Langmuir probes, which, besides providing the basic information about $\tilde{n}_e$ and $\tilde{\phi}_p$, do also provide the auto-and cross-correlation information required to evaluate the flux densities $\Gamma_{\perp}$ and Q. Single, double and triple probes have all been used in several tokamaks for this purpose.

The fluctuations in the density are normally measured by measuring the fluctuating component of the Ion saturation current, I_s^+, while the fluctuations from a probe measuring floating potential ϕ_f, are used to infer the fluctuations in local plasma potential ϕ_p. The floating potential and the plasma potential are normally related to each other through a relation of the type,

$$\phi_e \approx \phi_f + \frac{3kT_e}{e}$$

and the obvious difficulty with inferring $\tilde{\phi}_p$ by this method is that the temperature fluctuations, if present, would introduce a very large error. In most of the studies, however, it is assumed that $\tilde{T}_e / T_e$ is very small and its effect is neglected.

The temperature fluctuations in CALTECH Tokamak, have been measured, directly, using very fast sweep ($\leq$ 250 kHz) on a Langmuir probe and confirmed that $\tilde{T}_e / T_e \ll \tilde{n}_e / n_e$ or $e\phi_p/kT_e$ [16]. The temperature fluctuations have, however, been measured in several other tokamaks using a completely different technique first developed by Robinson and Rusbridge [17] for studies of the turbulent fluctuations in ZETA machine. The technique, briefly outlined in the following section, with some modifications, has been used in the study of Tokamak edge fluctuations by in TOSCA [18], in DITE [19] and in TEXT [20].

3.1. *Robinson-Rusbridge technique :*

The technique exploits the nonlinearity of the I-V characterstics of a double probe to simultaneously measure $\tilde{n}_e$, $\tilde{\phi}_p$ and T_e and the correlation functions $\langle \tilde{n}_e \tilde{\phi}_p \rangle$. The current in a symmetric, equal area double probe in plasma with a bias V, is given as

$$I = a.An_e \frac{2kT_e}{m_i} \tanh \frac{e(V - \phi_d)}{2kT_e} \qquad (8)$$

where ϕ_d is the voltage difference arising from the difference in floating potential between the tips of the probe, $a \approx 0.4 - 1.0$ and A is the area of the probe tip. In a turbulent plasma, fluctuations in the plasma parameters will give rise to the probe current fluctuations. Further the second order effects which do not vanish when averaged over time may effect the mean value of the current. The mean square of the fluctuating component of the probe current, $\tilde{I}$ can be written as :

$$\begin{aligned} \langle \tilde{I}^2 \rangle = \; & f_1^2 \langle \tilde{n}_e^2 \rangle + f_2^2 \langle \tilde{T}_e^2 \rangle \\ & + f_3^2 2 \langle \tilde{\phi}_p^2 \rangle + 2 f_1 f_2 \langle \tilde{n}_e \tilde{T}_e \rangle \\ & + 2 f_2 f_3 \langle \tilde{T}_e \tilde{\phi}_p \rangle + 2 f_3 f_1 \langle \tilde{n}_e \tilde{\phi}_p \rangle \end{aligned} \tag{9}$$

where the fluctuating quantities are normalised as follows :

$$\tilde{\imath} = \frac{\delta I}{I_s} \qquad \tilde{T}_e = \frac{\delta T_e}{T_e} \qquad \tilde{\phi}_p = \frac{e\,\delta\phi_p}{kT_e} \qquad \tilde{n}_e = \frac{\delta n_e}{n_e}$$

and the coefficients are the partial derivatives of the probe current with respect to the plasma parameters.

$$f_1 = \frac{n_e}{I_s} \left.\frac{\partial I_1}{\partial n_e}\right|_{T_e, \phi_d} = \tanh\left(\frac{x}{2}\right) \tag{10}$$

$$f_2 = \frac{T_e}{I_e} \left.\frac{\partial I}{\partial T_e}\right|_{n_e, \phi_d} = 0.5\left[\tanh\left(\frac{x}{2}\right) - x\,\mathrm{sech}^2\left(\frac{x}{2}\right)\right] \tag{11}$$

$$f_3 = \frac{kT_e}{eI_s} \left.\frac{\partial I}{\partial \phi_d}\right|_{n_e, T_e} = -0.5\,\mathrm{sech}^2\left(\frac{x}{2}\right) \tag{12}$$

$$x = \frac{eV}{kT_e}; \; I_s = aAn_e \sqrt{\frac{2KT_e}{m_i}} \tag{13}$$

For a double probe having a seperation, d, between the tips, which is much less than the coherence length and the wavelength of the turbulence, and is in poloidal direction we can write, $E_\phi = \phi_d / d$ and thus poloidal electric field fluctuations can be estimated in terms of the potential fluctuations.

Similarly the normalised mean deviation in the current, Δ_i, can be written in terms of the fluctuations in the plasma parameters as

$$2\Delta i = f_4 \langle \tilde{n}_e^2 \rangle + f_5 \langle \tilde{T}_e^2 \rangle + f_6 \langle \tilde{\phi}_p^2 \rangle + 2 f_7 \langle \tilde{n}_e \tilde{T}_e \rangle$$

$$+ 2f_8 < \tilde{T}_e\tilde{\phi}_p > + 2f_9 < \tilde{\phi}_p\tilde{n}_e > \tag{14}$$

Where

$$f_4 = \frac{n_e^2}{I_s}\frac{\partial^2 I}{\partial n_e^2}\Bigg|_{T_e,\phi_d} \qquad f_5 = \frac{T_c^2}{I_s}\frac{\partial^2 I}{\partial T_e^2}\Bigg|_{n_e,\phi_d}$$

$$f_6 = \frac{(kT_e)^2}{e^2 I_s}\frac{\partial^2 I}{\partial \phi_d^2}\Bigg|_{n_e,T_e} ; f_7 = \frac{n_e T_e}{I_s}\frac{\partial^2 I}{\partial n_e \partial T_e}\Bigg|_{\phi_d}$$

$$f_8 = \frac{kT_c^2}{eI_s}\frac{\partial^2 I}{\partial T_e \partial \phi_d}\Bigg|_{n_e} ; f_8 = \frac{kT_e}{eI_s}\frac{\partial^2 I}{\partial \phi_d \partial n_e}\Bigg|_{T_e}$$

At $x = 0$ only $f_3(x)$ is non-zero and hence only $< \tilde{\phi}_p^2 >$ contributes to $\tilde{i}^2$. At large $|x|$ dominant contribution comes from density fluctuations and a minor contribution comes from temperature fluctuations. Further f_1^2, f_2^2, f_3^2, and $f_1 f_2$ are symmetric about $x = 0$, while $f_1 f_3$ and $f_2 f_3$ are asymmetric. Coefficient f_2 has a zero at $x \approx 2.2$. Using these properties of the coefficients the amplitude of fluctuations in various parameters and their correlations can be estimated from the mean square current fluctuation amplitude. The density and temperature can be obtained from the average current; these estimates will, however, be subjected to errors due to fluctuations in ϕ_p and T_e. Vayakis and Robinson [19] have used an iterative scheme to overcome this difficulty. The fluctuation quantities, estimated from eq. (9) are used to estimate Δi from eq.(14) to correct for the errors in the average current and the process is repeated iteratively till parameters converge.

Alternatively, the model equation for $< \tilde{i}^2 >$ could be fitted to the measured current fluctuations vs the probe bias V curve, using nonlinear fitting routine [19,20]. The routine would adjust the six variational parameters to mimise the sum of the squared differences between the model equation and to observed data. Simultaneously, the average current could be corrected for contributions from fluctuations and the process iterated till the parameters converge. The method thus yields, the density, the electric field and the temperature fluctuations levels and the cross-correlations $< \tilde{n}_e\tilde{\phi}_p >$, $< \tilde{\phi}_p\tilde{T}_e >$ and $< \tilde{T}_e\tilde{n}_e >$. In practise the method is more accurate for $\tilde{n}_e$, and E ($\approx \pm$ 5%), and $\tilde{n}_e\tilde{E}$ ($\approx \pm$ 30%), but less accurate for $\tilde{T}_e$ and $\tilde{T}_e\,\tilde{n}_e$ ($\approx\pm$ 50%).

3.2. *Standard techniques using Statistical methods:*

Alternate to the technique outlined in the preceding section, standard techniques used in the analysis of random time series data [21-23] can, in principle, all be used to characterise the fluctuations in terms of auto- and cross-correlations in time and space domain, power spectral densities in frequency and wave-number domains, $S_{xy}(\omega)$ and $S_x(k)$, respectively, and spectral density of waves, $S(k, \omega)$. An array of spatially distributed Langmuir probes or a set of movable probes could be deployed for this purpose. In the CALTECH tokamak, for example, Zweben *et al* [24] used two appropriately positioned floating probes to measure the potential difference $\Delta\tilde{\phi}_p$, and the middle Langmuir probe aligned radially with the other two probes, to measure the density. The digitised signals were analysed using the correlation and Fourier transform techniques to obtain the spectral amplitudes of $\tilde{n}_e$ $\Delta\tilde{\phi}_p$ and $\tilde{\phi}_p$ and the phase and coherence between the two signals. The particle flux densities were then estimated from these quantities using relationship given by eq. (7). Levinson *et al* [25] estimated the particle transport in PRETEXT tokamak, directly from the correlations in $\tilde{\phi}_p$ and $\tilde{n}_e$ using the fast Fourier transform (FFT) based technique [26].

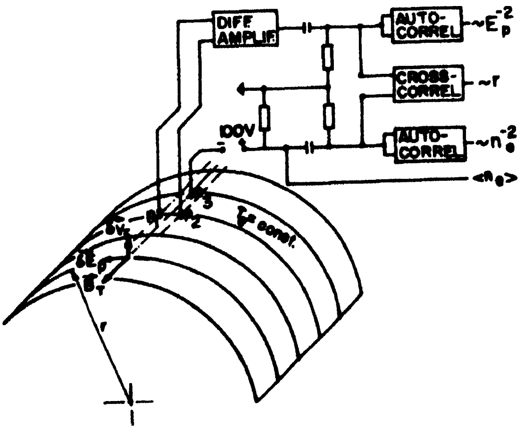

Figure 1. Probe arrangement used in CASTOR tokamak for study of fluctuations in edge plasma.

In a recent experiment in CASTOR tokamak [27] edge electrostatic turbulence was investigated using a poloidal array of triple probes (Figure 1) The tips of each probe were arranged in the form of a triangle. The two floating tips, seperated poloidally, were used for determining the poloidal electric field fluctuations, while the third negatively biased tip was used to monitor density fluctuations. The triple probe was connected to a three channel correlator yielding temporal evolution of the rms-values of $\tilde{n}_e$ and $\tilde{E}$ together with the correlation between them, enabling a time resolved measurement of the particle transport due to fluctuations.

3.3. *Wave number and frequency spectra from fixed probe pairs :*

In characterising fluctuations it is desirable to obtain spectral densities $S(\omega)$, and $S(\mathbf{k})$, or $S(\mathbf{k}, \omega)$. In a turbulent medium there does not exist a deterministic relationship between the frequency and wave number and hence identification of dispersion relation is not possible. While techniques for estimation of $S(\omega)$ are highly developed and widely used, several practical difficulties limit the capability to measure $S(\mathbf{k})$, or $S(\mathbf{k},\omega)$. In most of the cases estimation of $S(k)$, or $S(k, \omega)$ by simultaneous measurement of fluctuations at many points in space would be both prohibitively expensive and highly disruptive to the experimental phenomenon. Several approaches to this problem have been used each with its own difficulty and limitations.

One of the approaches involves scattering electromagnetic radiation (microwave or laser) from the fluctuating medium. Probe experiments offer important alternative to the scattering technique in that they provide localised measurements of the fluctuating plasma parameters. Many of the experiments, however, rely on point sources of data, usually from probes that are fixed in space. Iwama and Tsukishi [28] developed a correlation method of measuring the first and the second moments of $S(k,\omega)$, using fixed probe pairs. In this method the signals $n(R,t)$ and $n(R + r,t)$ from a fixed probe pair, are first passed through a band pass filter centered at frequency ω to obtain $n(R,\omega,t)$ and $n(R \pm r,\omega, t)$ and then a complex covariance function, $\gamma(r,\omega,t)$ defined as

$$\gamma(r,\omega.\tau) = \langle n(R + r, \omega, t + \tau) n(R.\omega, t) \rangle + J \langle \check{n}(R + r,\omega,t + \tau) n(R,\omega,t) \rangle$$

is calculated, where $\check{n}(R + r,\omega,t)$ is the Hilbert transform of $n(R,\omega,t)$, and the angular brackets denote ensamble average. Expressing $\gamma(r,\omega,0)$ in the polar form as

$$\gamma(r, \omega, 0) = A(r_1) \exp [j\Phi(r_1)] \tag{15}$$

it can be shown that the estimates of the first moment, $\bar{k}(\omega)$, and the second moment $\sigma_k^2(\omega)$, of $S(k, \omega)$ are given as

$$\bar{k}(\omega) = \frac{1}{r_1} \Phi(r_1) \tag{16}$$

$$\sigma_D^2(\omega) = \frac{2}{r_1^2} \left[1 - \frac{A(r_1)}{A(0)} \right] \tag{17}$$

where the probe seperation, $r_1 = |r|$ is appropriately small and the effect of the finite size of the probe is not significant. Iwama *et al* [29] have discussed the effects of small probe seperation on this formulation and used this technique in study of ion wave turbulence.

Beall *et al.* [30] have developed a technique for the estimation of wave number spectra using fixed probe pairs. They introduced the concept of *local wavenumber, K*, and gave a method of evaluating the local wavenumber spectral density, $S(K, \omega)$. The local wavenumber is the spatial analogue to the instantaneous frequency of the phase-modulated time domain signal. The technique is based on the premise that in a turbulent medium there is a stochastic relationship between the frequency and the wavenumber. If the raw data from two fixed probes is broken up in to many time intervals, the power, $P(\omega)$, associated with a given frequency interval ω_1 and $\omega_1 + d\omega$, and the phase difference, $\theta(\omega_1)$, between the two signals may be different in different realisations (time intervals) due to the stochastic nature of the turbulent medium. Thus from each realisation, i, the values of $P_i(\omega)$ and $K_i(\omega)$ ($= \theta\ (\omega)/$

Δx, Δx being the seperation between the probes), for various values of ω can be evaluated to yield $S_i\,(K,\omega)$. The average power associated with a given frequency ω and local wavenumber, K, is then defined as the local wavenumber spectral density, $S(K,\omega)$. The averaging is performed over successive realisations out of total realisations.

$$S(K,\omega)=\frac{1}{m}\sum_{i=1}^{m} S_i(K,\omega)$$

$S(K,\omega)$ is a good estimate of the conventional wavenumber spectral density $S(k,\omega)$ under the condition that the plasma is homogeneous along the direction of seperation of the probes, r, and the local wave amplitude, $a(r,\omega)$ and wavenumber $K(r,\omega)$, vary slowly over the wavelength *i.e.* they satisfy the WKB condition:

$$\frac{1}{a(r,\omega)}\frac{\partial^n a(r,\omega)}{\partial r^n} << K^n(r,\omega); \quad \frac{1}{K(r,\omega)}\frac{\partial^m a(r,\omega)}{\partial r^n} << K^m(r,\omega);$$

$$n,\, m = 1,\, 2,\, 3,\, \ldots\ldots\ldots\ldots$$

Beall *et al* [30] have further introduced the concept of the *conditional wavenumber spectral density* $s(K/\omega)$:

$$s(K/\omega)=\frac{S(K,\omega)}{S(\omega)} \tag{18}$$

where,

$$S(\omega)=\int S(K,\omega)dK$$

The functions $s\,(K/\omega)$ is like a probability density function and $s(K/\omega)\Delta K$ gives the fractional power at a frequency ω, due to the fluctuations in the range K and $K+\Delta K$. The first moment of the function, $s(K/\omega)$, gives the *satistical dispersion relation*, $\bar{K}(\omega)$, and the second moment a *wavenumber spectral width*, $\sigma_K(\omega)$, defined as

$$\bar{K}(\omega)=\int K s(K/\omega)dK \tag{19}$$

$$\sigma_k^2(\omega)=\int [K - \bar{K}(\omega)]^2\, s(K/\omega)dK \tag{20}$$

The wavenumber spectral width can be viewed as a turbulent broadening of the dispersion relation and is directly related to the frequency resolved correlation length :

$$L_c(\omega)=[\sigma_K(\omega)]^{-1} \tag{21}$$

$\sigma_K^2(\omega)$ is identical to the second moment (eq. 17, ref [28]). This technique has been used for study of edge plasma turbulence in PRETEXT tokamak [25] and in TEXT tokamak [31].

3.4. *Scattering techniques for density fluctuations :*

The scattering methods, using millimeter and sub-millimeter waves, are attractive as non-perturbing diagnostics which measure the frequency and the wavenumber spectra of density fluctuations directly while being able to access both the plasma edge and the core region. The spatial resolution is, however, limited. When an incident probe beam is scattered by the electron density fluctuations in the scattering volume, V_s, the scattered power, P_s, measured through a spectral window $\Delta\omega$, is given by [32]

$$P_s = P_i r_c^2 n_0 V_s \, S(k,\omega) \, \Delta\omega \Delta\Omega \tag{22}$$

where P_i is the incident power flux density, r_c is the classical electron radius, n_0 is the average density in the scattering region and $\Delta\Omega$ is the effective solid angle of reception. The wavenumber frequency spectral density, $S(\boldsymbol{k},\omega)$, of density fluctuations is given as

$$S(\boldsymbol{k},\omega) = \frac{1}{TV_s n_0} < | n(\boldsymbol{k},\omega) |^2 > \tag{23}$$

The frequency ω and the wavenumber $\boldsymbol{k}$ of the density fluctuations must satisfy the energy and momentum conservations laws :

$$\omega = \omega_s - \omega_i$$

$$\boldsymbol{k} = \boldsymbol{k}_s - \boldsymbol{k}_i$$

The subscripts i and s stand for the incident and the scattered waves respectively. The scattered radiation is detected by the mixing, in a photoconducting detecter, of the scattered light with a fraction of the light from the incident beam resulting in an IF signal which is at the difference frequency (which corresponds to the frequency of plasma fluctuations). Such a scheme does not produce any information concerning the direction of propogation of the fluctuations and is known as homodyne detection scheme. Heterodyne detection may also be employed and makes possible the determination of the wave direction $\boldsymbol{k}$. Heterodyne detection provides several advantages for the study of small angle scattering. The frequency spectrum of the density fluctuations is measured directly from the frequency specturm of the detector signal. Using heterodyne detection, fluctuations with arbitrary long wavelengths can be studied since for these wavelengths the optical apparatus is simply an interferometer.

With the power sources in the microwave or the mm-wave region well established, several wave scattering experiments have been carried out in various tokamaks [33-36]. Microwaves, CO_2 lasers and far infra red (FIR) lasers have all been used for this purpose. The microwave scattering measurements are, however, severely influenced by cut-off or diffraction effects at higher densities ($\geq 10^{13}$ cm^{-3}). The CO_2 laser scattering technique is by now well established [35]. It, however, suffers from the disadvantage that its spatial resolution along the incident laser beam is poor due to small scattering angle. The limitation could, however, be overcome by using a cross-beam correlation technique [37]. The range of plasma densities which can be coveniently studied is from 10^{10} cm^{-3} to 10^{17} cm^{-3} The FIR lasers are capable of simultaneously providing localised measurements (Δx = 1.5 – 3.0 cm) with good wavenumber resolution ($\Delta k \leq 3$ cm^{-1}). In FIR scattering experiments the scattering angle and the region can be selected fairly freely [36,38-39].

Ritz *et al* [40] have used both, the Langmuir probes and the multichannel FIR laser scattering, to characterise the turbulence in the edge region of TEXT tokamak. By demonstrarting agreement for these two independent diagnostic schemes, a connection can be made between the density fluctuations observed in the plasma interior and more complete set of data in plasma edge region. Their results indicate agreement on all points which could be compared, including the frequency and wavenumber spectra, the fluctuation dispersion and the absolute magnitude of $\tilde{n}_e$.

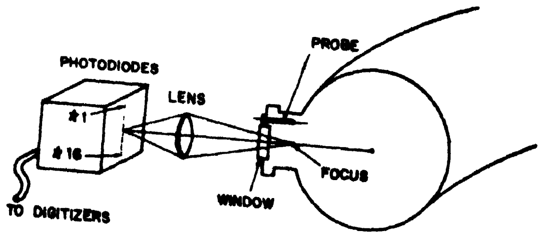

Figure 2. Optical imaging system used for monitoring visible intensity flbctuations in CALTECH tokamak [41].

3.5. *Optical imaging of density fluctuations :*

Visible light fluctuations are well correlated with the edge density fluctuations measured with a Langmuir probe as has been demonstrated in CALTECH tokamak [41]. A 16 channel photodiode array used to monitor the visible fluctuations allows for quantitative analysis of the edge turbulence patterns and the non-perturbing nature of the measurements makes it possible to use this as a diagnostics of edge plasma fluctuations in tokamaks. Good spatial resolution in the region of interest can be obtained by focusing it to the photodiode array. Each photo-diode views a cone contered on the focal point (Figure 2) and extending through the plasma. The signal is thus composed of an average emission in its direction over this cone. The area which the diode views, however, expands away from the focal point and, therefore, the contributions of small-scale structure away from the focus will be spatially averaged giving rise to mainly a constant level to the diode signal. The diode array could, therefore, be used to effectively monitor the small-scale fluctuations from the region in neighborhood of the focal plane of the array by monitoring the fluctuating current in the diodes.

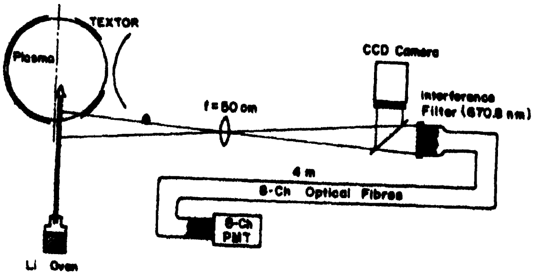

Figure 3. Schematics of the thermal neutral lithium beam probe system used for study of density fluctuations in SOL of TEXTOR tokamak [45].

Visible imaging of edge fluctuations has also been carried out in TFTR tokamak [42,43] using a gated, intensified video camera from the outer mid-plane along with a periscope system.

3.6. Thermal lithium probe for density fluctuations :

Thermal lithium atomic beam probes can be used to measure simultaneously the radial profile of electron density and its fluctuations in the scrape-off layer (SOL) of the plasma. The technique is non-perturbing. The probe beam could be generated by heating lithium metal at 550 — 580°C in an oven. The rate of local photon emission from the lithium resonance line (6708Å) due to electron impact excitation yields a measure of $n(r)$ and $\tilde{n}_e(r)$. In the studies conducted by Komori *et al* [44] the local fluctuation levels of the photon emission, $\tilde{I}/I$, were found to be equal to local electron density levels, $\tilde{n}_e/n_e$ in the region where the attenuation of the neutral beam was small and T_e was in the range of 10-100 eV. The high frequency response was found to be well above 2 MHz. Density fluctuations in the SOL of the TEXTOR tokamak have been studied using this technique [45]. A thermal beam of 1 cm diameter along with an eight channel optical detection system (Figure 3) was employed. The spatial resolution in each channel was ≈ 5 mm, and the distance between adjacent channels was 7.5 mm. The signals were digitised at 2 MHz or 400 kHz using transient digitisers obtaining resolutions of ≈ 2 kHz and ≈ 0.4 kHz respectively. The analysis was carried out using FFT algorithms. The frequency and wave number spectra of density fluctuations obtained in TEXTOR by this technique were in good agreement with those observed in other tokamaks. This agreement confirmed the validity of the thermal neutral beam probing technique.

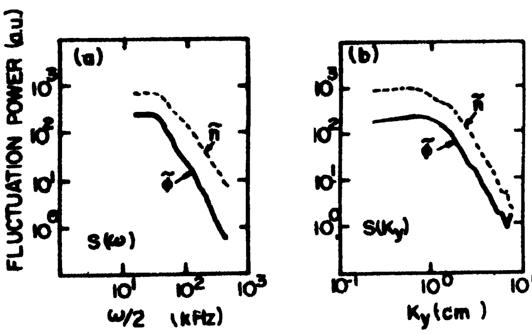

Figure 4. Fluctuation spectra obtained on PRETEXT [25]; (a) frequency spectra for density and potential fluctuations; (b) wave number spectra for density and potential fluctuations.

4. Characterstics of the fluctuations :

The measurement of the edge fluctuations from various tokamaks exhibit a general consistency. The results indicate a broadband nature of the fluctuations spanning a wide range of frequencies and poloidal wave number k_θ. Examples of the spectra measured in PRETEXT [25] are given in Figure 4. The main power lies in the range of 10-100 kHz and 0.1 - 10 cm^{-1}. The wave number along the field line $k_\parallel$ is typically much less than k_θ [9,11]. The measurement on TEXT [46] and TFTR [43] indicate a mean $\bar{k}_r = 0$. The power spectrum varied as ω^{-n} with $n \approx 2-4$ [9,24]. The wave number spectrum measured on TEXT using probes and FIR scattering [40] is shown in Figure 5. The spectrum indicates $\Delta\omega/\omega \approx \Delta k_\theta/k_\theta \approx 1$. The frequency broadening indicates the turbulent nature and it has been shown [46] that three wave interactions play important role. The fluctuations propagate in electron drift direction for radii smaller than the limiter radius and in ion drift direction at radii greater than the limiter radius [31]. The measured phase velocity fits well the theoretical predictions [47], $\tilde{v}_{ph} = v_{de} - E_r/B$ with $v_{de} = kT_e/eB_TL_n$ where L_n is the density scale size.

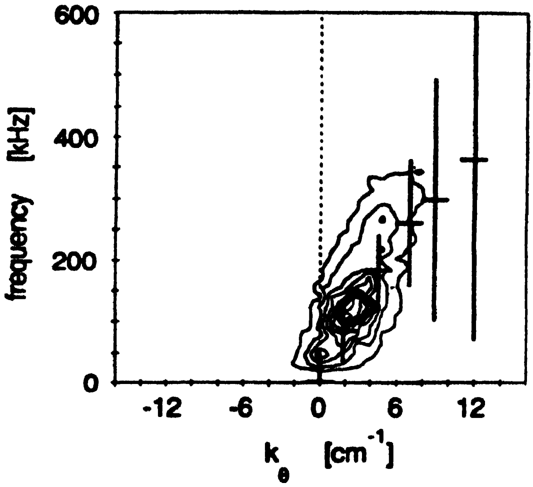

Figure 5. Wave number spectrum measured on TEXT [40] using Langmuire probes and FIR scattering.

The radial variation of the fluctuations in the edge region has been measured in CALTECH [16], MACROTOR [48], TOSCA [18], DITE [19], PRETEXT [25], TEXT [49] and ASDEX [50]. Density fluctuation levels increase with increasing radius reaching $\tilde{n}_e/n_e \approx 1$ in the edge region. Radial profiles collected over a number of shots in steady state ohmic discharges on TEXT [49] are shown in Figure 6. The rms values are for fluctuations upto 500 kHZ and k_θ- upto 30 cm^{-1}. Relative fluctuations are substantial for $r/a \geq 0.9$. The Boltzman relation is not satisfied :

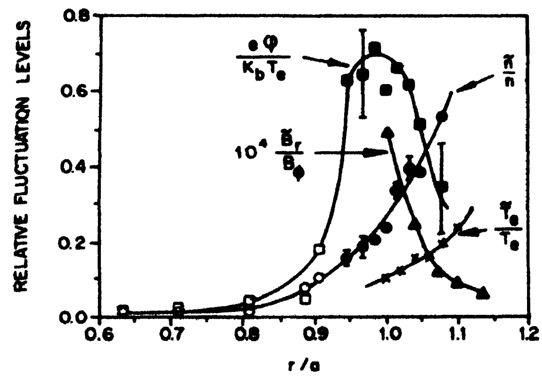

Figure 6. Radial density potential and temperatue fluctuation profiles in edge region of TEXT [49].

$$\frac{\tilde{n}_e}{n_e} \neq \frac{\tilde{\Phi}_p}{kT_e}$$

The results are characterstic of all tokamak edges.

Relative amplitude of temperature fluctuations is different in different tokamaks. The measurements in CALTECH [16] give $\tilde{T}_e/T_e \approx 0.15$ while the results from TOSCA [19] indicate

$$\frac{\tilde{T}_e}{T_e} < < \frac{\tilde{n}_e}{n_e}; \frac{\tilde{T}_e}{T_e} \quad 0.01$$

Results from ISX [15], DITE [18] AND TEXT [20] indicate large temperature fluctuations :

$$\frac{\tilde{T}_e}{T_e} \approx 0.4 - 0.5 \frac{\tilde{n}_e}{n_e}$$

The temperature fluctuation profile in TEXT, shown in Figure 6, measured behind the limiter using statistical method, has same radial shape as the density fluctuation profile. It thus appears that the temperature fluctuations may or may not be substantial enough. Impurity level may play important role in determining the level of temperature fluctuations in the edge region [52].

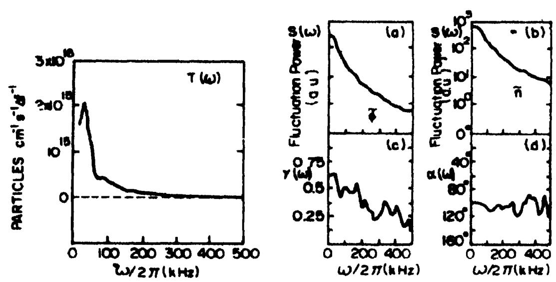

Figure 7. Spectrally resolved particle flux observed in PRETEXT edge region due to electrostatic fluctuations [25].

5. Particle flux due to fluctuations

Fluctuation induced particle and energy fluxes have been measured in the edge region of several tokamaks [16,24,25,53,54]. The particle flux is radially outwards and most of the flux is contributed by the fluctuations in the frequency range below 100 kHz as illustrated in Figure 7 which shows the spectrally resolved particle flux measured in PRETEXT [25]. The coherence between $\tilde{n}_e$ and $\tilde{\Phi}_p \approx 0.5$ and the phase angle $\alpha(\omega) \geq 90°$. In observations on TEXT [53] it has been established that the total particle flux in the edge plasma is due to the electrostatic fluctuations. The results from other tokamaks are in conformity with this.

6. Summary

The basic experimental information available from several tokamaks indicates that the electrostatic fluctuations in the edge plasma varies strongly as a function of the radius reaching relative amplitude of ≈ 100%. The fluctuations span a wide range of frequencies and poloidal wave numbers. The main power lies in the range of 10-100 kHz and 0.1-10 cm^{-1}. The parallel wave numbers are in general much smaller than the poloidal wave numbers. The electrostatic fluctuations appear to account for total particle flux in the edge region.

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