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Visible imaging of turbulence in the SOL of the Alcator C-Mod tokamak

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Abstract

Measurements of fluctuations in the scrape-off layer (SOL) of Alcator C-Mod plasmas were made using visible emission from the plasma edge. Line emissions from a local gas jet of He atoms were imaged along radially separated, toroidally viewing chords and provided local measurements ($\Delta R, \Delta Z = 3.4$ mm, $R\Delta\phi \sim 20$) mm) of density fluctuations. The RMS emission fluctuation amplitudes, normalized by the average emission, ranged from 10% to 60%, depending on distance from the separatrix, and increased sharply beyond $\rho_{\text{from LCFS}} = 20$ mm. These intensity fluctuations imply that radial profile of the normalized RMS density fluctuations varies from ~20% to 90%. Typical fluctuation spectra show turbulence out to frequencies of ~150 kHz, although most of the spectral power is below 20 kHz. The radial correlation length for the <20 kHz fluctuations is ~7 mm. No essential differences were seen in the SOL fluctuations when plasmas with 'Enhanced D_α' (EDA) H-mode confinement were compared with those having L-mode confinement. In addition, fluctuations in 'natural' D_α light, due to recycling at an outboard poloidal limiter, were imaged by a gated fast-framing camera and provided measurements of the poloidal size scale of the SOL fluctuations. Snapshots of D_α emission were obtained with exposures of 2 and 10 μs. Typical fluctuation size in the poloidal dimension was 0.01–0.03 m. These striations/fluctuations were randomly located in the successive gated frames taken at 1000 Hz, as expected for edge turbulence. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

This work reports on the characteristics of the turbulence, in this case density fluctuations, measured in the scrape-off layer of Alcator C-Mod [1] discharges. The diagnostic technique employed uses light emission from a stream of He atoms as the probe of the turbulence. General motivation for studies of edge turbulence comes from observations that edge transport barriers can improve energy confinement in the core, e.g. in so-called H-mode confinement regimes, as well as from the role played by turbulence in determining the SOL power-handling capability. These observations indicate the importance of diagnosing, understanding, and ultimately controlling the anomalous radial particle and energy transport at the plasma edge. The area concerned with SOL turbulence is a mature field of investigation with numerous studies in the literature. An excellent review by Endler ([2], and references therein) discusses the current state of understanding. Anomalous edge transport is believed to be due primarily to broadband turbulence, and the dominant electrostatic turbulence results in density fluctuations [3,4]. The wavelengths of the fluctuations are such that $k_{\text{perp}}\rho_i < 1$. Langmuir probes have been and remain the primary diagnostic

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tool, but optical methods have been used successfully since the early 1980s [5].

Some of the general understanding on this subject, as reported in [2], we will use as assumptions, which will underlie the interpretation and motivations of this work. Explicitly we assume: (1) that density fluctuations lead to radial particle transport, since the phase difference between the density fluctuation and the fluctuation in v_r is typically between 0.3 and 0.5π; (2) that edge turbulence is important in the plasma particle and energy balance, since, within a factor of about two, it is generally found that the transport calculated from the measurement of the fluctuations in density, n^{RMS}, and radial velocity, v_r^{RMS}, is consistent with the global particle balance; and (3) that the wavelengths parallel to the magnetic field of the fluctuations are long ($\sim$ meters), compared with typical poloidal wavelengths (1–4 cm in most tokamaks) and radial correlation lengths of 0.5–2 cm.

This work is motivated by multiple reasons. Alcator C-Mod is a high density, high field tokamak, with n_e up to $\sim 1 \times 10^{20}$ m^{-3} in the SOL and $B_t = 4.1$ T in the outer midplane SOL. It is worthwhile to compare fluctuation characteristics in this unique device with those found in other experiments. In addition, there is interest in the edge transport during an attractive enhanced confinement regime found in C-Mod called 'Enhanced D_α' (EDA) H-mode. In EDA H-mode, energy confinement is comparable (with $H_{ITER89P} \sim 2$) to the best confinement observed in C-Mod, but particle and impurity confinement is significantly reduced, and no larger ELMs occur [6]. The beneficial increase in particle transport is probably a result of an observed quasi-coherent mode located just inside the separatrix [7]. In another area, there is the observation on C-Mod that, even in L-mode confinement plasmas, particle transport increases with radius in the region just outside the separatrix where there is a sharp density gradient [8]. And finally, there is the observation that recycling and fueling for the plasma in the main chamber is determined mainly by perpendicular particle fluxes. The role (in the main chamber particle balance) played by parallel flow to and from the divertor is typically secondary [9]. The mechanism by which this occurs is still not clear and we attempt here to find a connection with these observations in the examination of the radial structure of the SOL fluctuations.

2. Radial measurements of fluctuations

2.1. Experimental technique and fluctuation characteristics

The experimental technique consists of viewing, toroidally and with high radial spatial resolution ($\Delta R = 3.4$ mm), an atomic beam of He atoms injected from a gas jet into the outer SOL. Fig. 1 shows a side view of system with the gas nozzle located between the top and bottom halves of a split poloidal limiter. The end of the nozzle is 15 mm beyond the flux surface touching the split limiter and, as such, is typically only $\sim$40 mm beyond the separatrix. Not shown in Fig. 1 are the in-vessel telescope and the 14-fiber array used to image the radial section of the gas jet.

When room temperature He is puffed from the jet, intensity fluctuations in the $3^3D - 2^3P$ transition (wavelength = 587.6 nm and the brightest line in the He I spectrum) are measured along three of the 14 views. The light from the in-vessel fiber array is brought out of the tokamak via fibers, imaged through an interference filter, and focussed onto a photodiode. A high-gain broadband amplifier similar to those used in beam emission spectroscopy experiments [10] amplifies the detected photocurrent. The remaining 11 views are used to measure (with a different spectrometer system) the radial profiles of: (1) electron density, (2) electron temperature, and (3) He I emission. n_e, T_e are derived from the measured line ratios among the 668, 706, and 728 nm He I lines, following the formalism of Schweer et al. [11].

Use of the close-proximity He gas jet has the advantage that measurements are essentially 'crossed-beam' and therefore well localized. The measured to-

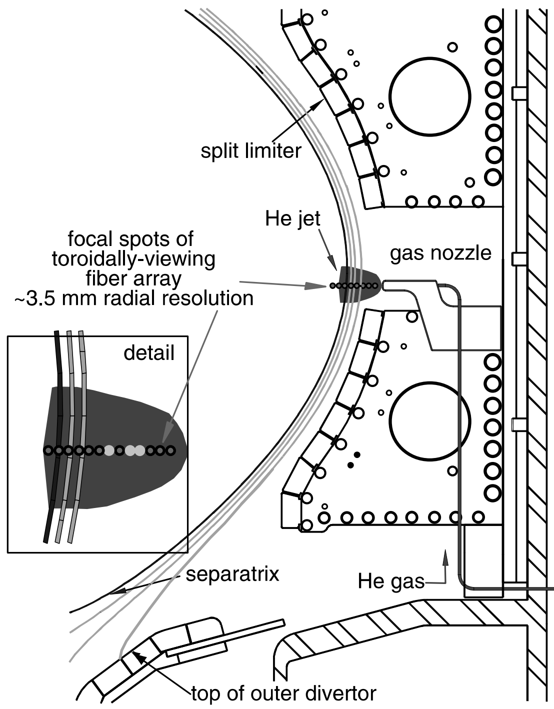

Fig. 1. Side view of gas jet and schematic of intersection between He beam and toroidal sightlines.

roidal extent of the D_2 emission cloud (when D_2 is puffed) is only 15–20 mm. If the He I cloud is similar in extent, this means that: (1) radial smearing along the sight line resulting from the toroidal curvature is negligible, and (2) emission is sampled from a flux tube of ~7 mm in poloidal extent (since the flux tube crosses the purely toroidal sightline at a 10–15° angle), and this is far smaller than the observed poloidal wavelengths (see Section 3).

We have examined the fluctuation characteristics from a number of discharges that undergo back-transitions from EDA H-mode confinement to L-mode confinement. Outside of $\rho \sim 4$ mm, there is no obvious difference between the two confinement modes as regards the SOL fluctuations. For example, the frequency spectra of the intensity fluctuations at $\rho = 11$ mm during EDA H-mode and L-mode are compared in Fig. 2. (The ρ coordinate is used throughout as the radial distance outside the seperatrix [1] at the outside midplane. If the measurement is not made on the midplane, its location is mapped along flux surfaces to the midplane and assigned a ρ.) Note that, although the fluctuation amplitudes are above the background out to ~150 kHz, most of the spectral power is at frequencies <20 kHz. A related quantity, the autocorrelation function of the intensity fluctuations at a given radius, also shows no significant change across the EDA-to-L-mode transition, although there is a systematic decrease with increasing ρ in the 1/e time delay of the autocorrelation function, as shown in Fig. 3. Physically this means that the time the fluctuation feature remains in the field-of-view decreases with increasing ρ and is probably due to increased turbulence.

The radial size of the fluctuations can be estimated by calculating the cross-correlation function among signals sampling differing radial positions. When this is done, it found that the typical radial correlation length is ~7 mm. A non-zero phase is observed between signals from different radii, implying a ~10^2–10^3 m/s radially outward propagation velocity. However, since we are observing at one poloidal position only, poloidal propagation of structures tilted in the poloidal plane and radial propagation cannot be distinguished [12].

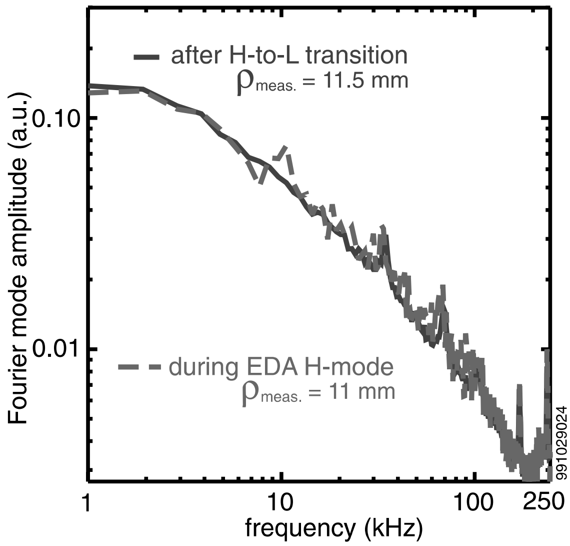

Fig. 2. Frequency spectrum of SOL fluctuations during EDA H-mode and L-mode confinement.

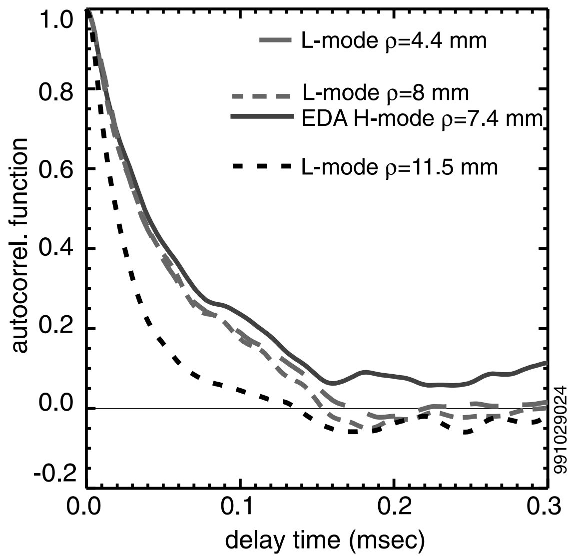

Fig. 3. Autocorrelation function of SOL fluctuations at different radii and during EDA H-mode and L-mode confinement.

2.2. Relating intensity fluctuations to density fluctuations

At densities below 10^{18} m^{-3} the intensity of the 587.6 nm line is proportional to the density of the electrons responsible for its excitation. However, at the higher densities found in the SOL of Alcator C-Mod, the radiative decay rate is no longer much larger than collisional depopulation processes and the intensity dependence on density is less than linear. We have used the collisional-radiation model CRAMD [13] to predict

[1] We have had to shift the midplane position of the separatrix (as determined from the magnetic reconstructions) inward by 7 mm. This was done in order to match the edge n_e and T_e profiles, as measured spectoscopically at the midplane and by a horizontally scanning probe near the midplane, with those from Thomson scattering, which are measured at the top of the plasma.

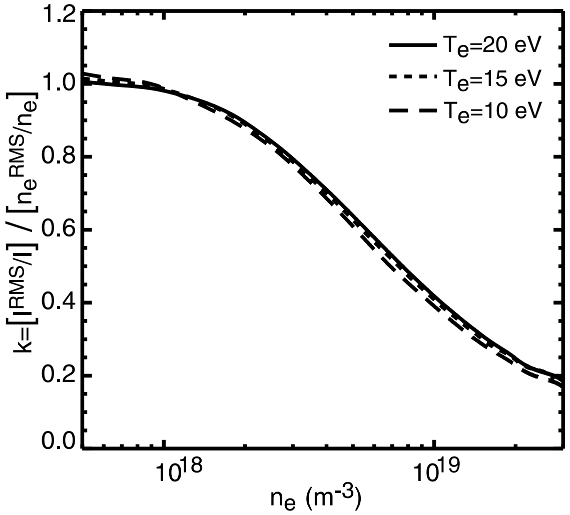

Fig. 4. Function $k(n_e)$ vs. n_e, relating the intensity fluctuation in the He I 587.6 nm line to the density fluctuation.

the density (and temperature) dependence of the 587.6 nm line intensity in order to relate the intensity fluctuation level, I^{RMS}/I, to the quantity of greater interest, n_e^{RMS}/n_e. The factor, $k(n_e) = [I^{RMS}/I]/[n_e^{RMS}/n_e]$, relating the two is shown in Fig. 4. It is clear that at densities $>3\times10^{18}$ m^{-3} the intensity fluctuation responds less for a given density fluctuation. The less-than-linear dependence of the intensity on the density requires that the local density be known in order to unfold the density fluctuation from the intensity fluctuation. This density measurement is made by interpolating the densities measured spectroscopically (see above) along views which are adjacent to those used for the intensity fluctuations.

In order to measure the radial profile of the intensity (and density) fluctuations using only three of the 14 views, the position of the separatrix was scanned dynamically during ohmic, L-mode plasma discharges. The radial profiles of I^{RMS}/I vs ρ and n_e^{RMS}/n_e vs ρ were constructed from ρ scans during four similar discharges and are shown in Fig. 5(a) and (b). Outside of $\rho =$ 20 mm the fluctuation level increases up to $\sim$80% in n_e^{RMS}/n_e. It should be noted that the flux tubes from this region do not end on local outboard limiters, but terminate on the top of the lower, closed divertor (see Fig. 1) and the inner wall (a toroidal limiter). The position where the fluctuations start to increase does not seem to be correlated with the nearest termination point of the local flux tube. This increasing fluctuation level is qualitatively consistent with very large outward radial He transport found for the far SOL in C-Mod ($\rho > 30$ mm) in [14]. For 10 mm $< \rho <$ 20 mm, there is a region where the normalized fluctuation level is $\sim$20–40%. This is in a region with a relatively small density gradient, and the fluctuation level is typical of that measured in the SOLs of other tokamaks [2,15,16]. Between $\rho \sim 4$ mm (where the emission becomes too weak for an accurate measurement) and $\rho \sim 10$ mm, the intensity fluctuation level shows a small increase with decreasing ρ. Since the densities are above 3×10^{18} m^{-3} in this region, this implies a relatively strong increase in density fluctuation level, as shown in Fig. 5(b). This trend is *opposite* that described for the 'effective diffusion coefficient' ($= \Gamma_{perp}$/(grad n)) in this region of SOL in [8]. In [8] it is found that the radial flux and particle source are approximately constant in this region where there is density gradient, implying a 'D_{eff}' which decreases sharply from $\rho \sim 10$ mm to low values ($\sim$0.05 m^2/s) at the separatrix. Without more information we cannot reconcile these two observations, since the fluctuation-

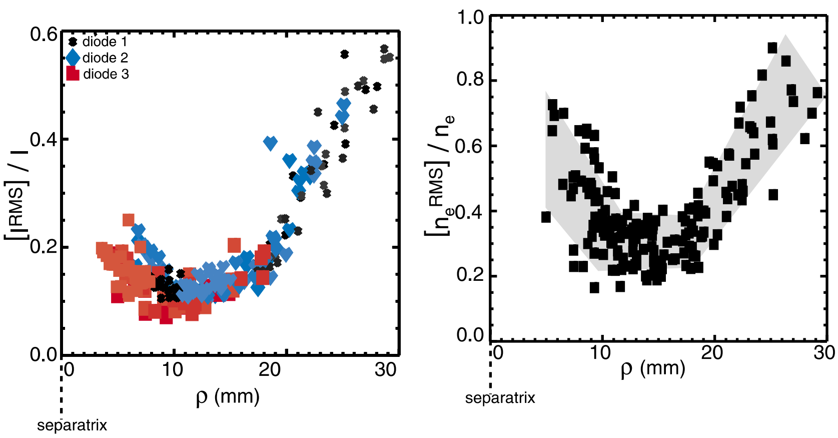

Fig. 5. (a) Radial profile of normalized He I intensity fluctuations. (b) Radial profile of normalized density fluctuations determined from intensity fluctuation profile 5(a).

driven transport is $\langle n_e^{RMS} v_r^{RMS} \rangle$ and 'D_{eff}' does not separate diffusive and convective effects. More will be said about this in Section 4.

3. Poloidal measurements of fluctuations

The experimental technique for examining the poloidal characteristics of the turbulence consists of viewing the plasma column (toroidally) with a digital camera whose exposure is gated for a time less than or equal to 10 μs. Within the cameras field-of-view is the edge of an ICRF-heating antenna, located on the outboard side of the plasma. There is strong D_α emission at this antenna limiter due to local recycling there. With the camera filtered for D_α light, the emission is observed to be spatially modulated poloidally and appears as striations. This is attributed to density fluctuations within flux tubes passing through the recycling region, since successive frames recorded every 1 ms show that the poloidal pattern of the striations is randomly oriented. This would not be the case if the pattern were due to a structural variation in the limiter causing differences in recycling. Radial measurements of D_α made using the gas jet described in Section 2 indicate that the radial location of the D_α light at the antenna limiter is probably at $\rho \sim$ 10–20 mm. The observation technique and the features of the striations are similar to those described in [17]. Since the striations are illuminated by recycling in the region near the antenna limiter, the intensity variation along a line that follows the curvature of the limiter image shows the poloidal structure of the fluctuations. Plots of the intensity variation along the poloidal curvature of the limiter are shown in Fig. 6. In 6(a) two 10 μs exposures from successive frames, taken 1 ms apart, are shown. There is no correlation of fluctuations in frames taken at 1000 Hz, indicating that the autocorrelation time is short compared to 1 ms. Fig. 6(b) shows cases for which the exposure time was 2 μs. The full-widths-at-half-maxima (FWHM) of the striations seen with 10 μs exposures are between 15 and 35 mm, while those in the 2 μs exposures are between 10 and 30 mm. (The lower limit on the spatial resolution is ~5 mm, set by the camera system.) Thus the characteristic size in the poloidal dimension for the fluctuations is 0.01–0.03 m.

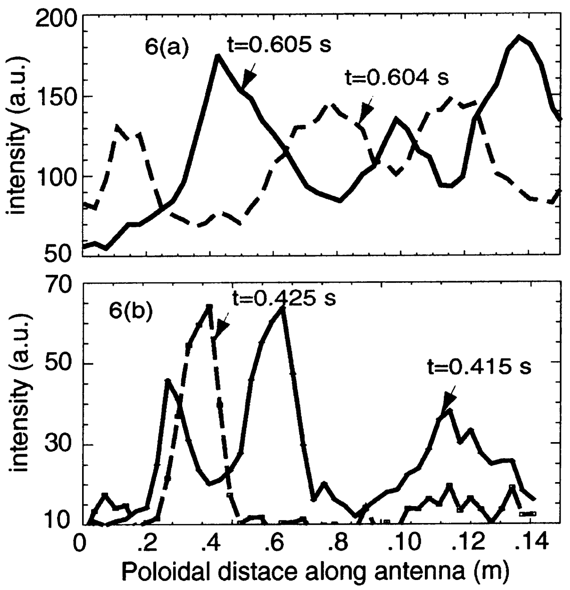

Fig. 6. D_α intensity vs. poloidal distance through the antenna-limiter recycling region: (a) 10 μs exposure, (b) 2 μs exposure.

4. Discussion and summary

In reviewing the characteristics of the fluctuations found in the C-Mod SOL, we find no great difference between them and those found on other tokamaks, stellarators, and the spherical torus, NSTX [18]. The frequency spectra are similar [4,15,18]. The autocorrelation time, 30–70 μs is similar to, although somewhat longer than the fluctuation *lifetimes* (10–50 μs) observed elsewhere [4]. The radial correlation length, ~7 mm, is in the range, 5–20 mm, found on other machines [2]. The radial profile *outside of* $\rho = 10$ mm has a similar shape, although in the far SOL, the ~80% level found on C-Mod (and DIII-D [16]) is higher than on other devices. The fluctuation size in the poloidal dimension, found from the camera images (0.01–0.03 m), is squarely in the 0.01–0.04 m range quoted in [2] for the typical poloidal size. All of these observations suggest that the turbulence does not scale strongly with magnetic field, since these observations are common on machines with fields as low as 0.3 T (NSTX) and as high as 4.1 T (C-Mod) [2,18].

The observation that the fluctuations outside of $\rho \sim 4$ mm are similar in both EDA H-mode plasmas and in L-mode plasmas suggests that the edge barrier responsible for the EDA edge pedestals does not extend far enough out in the SOL to affect the turbulence there. This implies that the SOL turbulence adjusts to what flows out across the separatrix, rather than determining it. In addition, the quasi-coherent mode, thought to be responsible for the increased particle transport seen in EDA H-mode plasmas, also does not appear to affect the SOL fluctuations outside of $\rho = 4$ mm.

The radial profile of normalized density fluctuations between $\rho = 4$ and 10 mm is not similar to that found in some other machines. In C-Mod the normalized fluctuation level is seen to be decreasing with increasing ρ from as much as 80% to ~30% over that region. On TEXTOR and ASDEX, the level is constant or increases with increasing ρ [4,15]. In DIII-D L-mode plasmas there is a decrease in n_e^{RMS}/n_e with ρ (from 50% to 40%) in the initial ~15 mm of the SOL [16], which is qualitatively similar to C-Mod. The reasons for the differences are not clear. We can speculate about a connection between these results and the observation that perpendicular transport in the SOL dominates the main chamber recycling in C-Mod [8,9]. Although the fluctuation level beyond $\rho = 20$ mm is high, there is probably not enough density there to affect recycling significantly. In the $\rho < 10$ mm region the density, its gradient, and n_e^{RMS} are large, and perpendicular transport caused by high levels of turbulence in this region would probably affect the global recycling. If the similarities in the fluctuation level and profile between C-Mod and DIII-D L-mode are extrapolated to values of turbulent radial flux, which were measured in DIII-D [16], then the turbulent transport is large ($\sim 0.7D_{Bohm}$) in this region and is approximately the level required for dominant main-chamber recycling in C-Mod [8]. Of course, this has not been shown quantitatively. Nonetheless, the observations are qualitatively consistent in a general way.

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