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Radial Correlation Length Measurements in ASDEX Upgrade

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Introduction Fluctuations and turbulence are believed to play an important role in anomalous transport of heat and particles in magnetic fusion devices, and hence their characterization is important. Specifically, the radial and poloidal correlation lengths of turbulence (L_r and L_p) may be used to define the spatial size of turbulent eddies. L_r has been measured using a variety of diagnostics, the most common being correlation reflectometry. In this paper, L_r measurements obtained using the newly developed technique of correlation Doppler reflectometry are presented. This technique, where two microwave beams are launched into the plasma from the same tilted antenna, has been developed on ASDEX Upgrade to provide simultaneous measurement of the perpendicular velocity of the turbulence ($u_\perp$), the radial electric field (E_r), its shear ($\partial E_r/\partial r$) and the radial correlation length of the turbulence (L_r). Previous work has focused on the former three measurements [1, 2, 3, 4] while the current work concentrates on L_r measurements. Since the Doppler reflectometer probes a specific turbulence wavenumber $k_\perp$, it is necessary to demonstrate that the diagnostic measures the true L_r. This has been investigated using a two-dimensional Finite Difference Time Domain (FDTD) code to simulate the Doppler reflectometer response and to recreate the experimental L_r measurements. This paper presents examples of experimental L_r measurements from correlation Doppler reflectometry at the plasma edge along with simulation results from the 2D code.

Technique The correlation Doppler reflectometry system on ASDEX Upgrade consists of two identical V-Band heterodyne reflectometers. The two Doppler reflectometer channels are connected to the same antenna pair so that they launch microwaves with the same line of sight simultaneously into the plasma. The microwaves have different launch frequencies (f_1 and f_2) and therefore reflect from different radial positions in the plasma (r_1 and r_2). For L_r measurements, the frequency of one reflectometer channel f_1 is held constant while the frequency of the second f_2 is stepped away. Here, a stair case every 50ms with a frequency difference between the two channels starting at 0.1GHz (to avoid any cross talk between the two channels) and increasing logarithmically was found to be sufficient. Cross correlating the two Doppler shifted reflectometer signals (i.e. the complex Doppler reflectometer signals $I + iQ = Ae^{i\phi}$, see [3]) gives the coherence between the two signals as a function of their frequency separation. The density profile n_e is required to translate the frequency separation to a radial separation $\triangle r$. The radial separation when the coherence drops to 1/e gives a measure of the spatial correlation of the turbulence (designated the radial correlation length, L_r) for the particular turbulent wavenumber $k_\perp$ studied. (The wavenumber is selected by the tilt angle between the plasma flux surface normal and the incident microwave beam.)

Experimental Results The first example examines the effect of plasma heating on L_r. During Ohmic ($1.5 - 1.6$s), L-mode ECRH heated ($2.5 - 2.6$s) and L-mode NBI heated phases ($6.3-6.4$s) of discharge #18707, profiles of E_r and L_r were measured simultaneously and are shown in figure 1. (Details describing the technique used to measure E_r and its associated shear with the Doppler reflectometer diagnostic can be found in references [3, 4].) The edge E_r profile becomes more negative during the NBI heated phase due to the increasing electron temperature and density gradients at the edge pedestal. The increase in $|E_r|$ is linked to a decrease in L_r as shown in figure 1. NBI heating is observed to decrease the edge radial correlation lengths in comparison with ECRH heating.

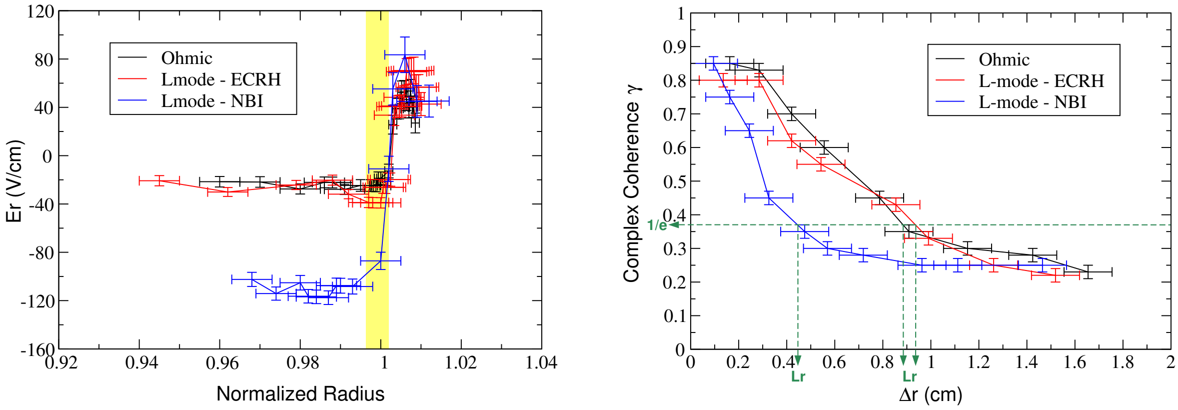


Figure 1: *E_r profiles and corresponding L_r measurements obtained during discharge #18707 using X-mode polarization. The yellow shaded region displays the radial position where L_r was measured. During the NBI heated phase, the edge E_r becomes more negative and the radial correlation length decreases.*

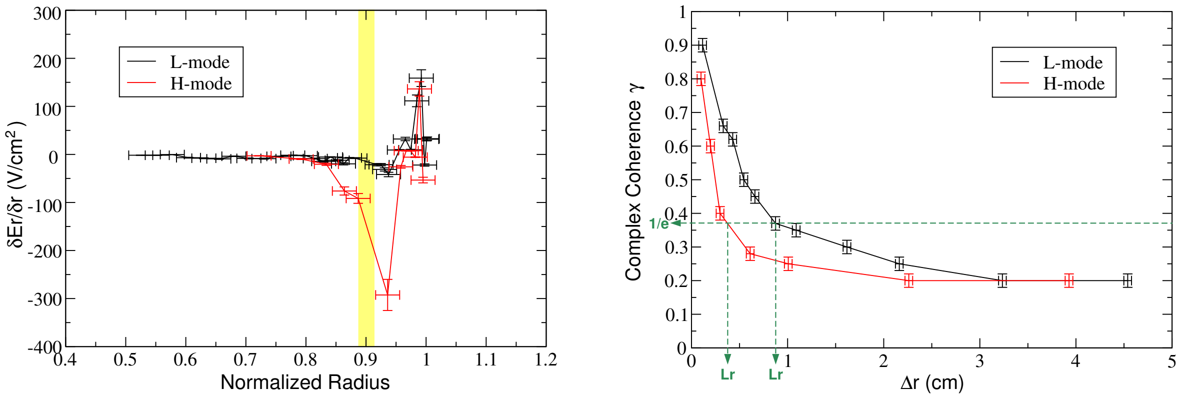


Figure 2: *The simultaneous measurement of E_r shear and L_r in an L-H transition discharge (#19151) using O-mode polarization. L_r was measured at $\rho_{pol} \approx 0.90 \pm 0.02$, marked by the yellow shaded region. The result shows a reduction in L_r in the region of high E_r shear.*

Several theories exist which link E_r and its shear to L_r. For example, the Biglari Diamond and Terry (BDT) model [5] claim that an increase in absolute E_r shear suppresses density fluctuations and stabilizes the turbulence, thereby decreasing L_r. This can be seen in the following example. Figure 2 shows the E_r shear profiles along with L_r measurements during L-mode and H-mode phases of discharge #19151. The E_r shear profiles are positive around the SOL region, becoming negative in the pedestal region. The edge E_r shear in the H-mode phase reaches a minimum of $-(290 \pm 30)\mathrm{Vcm}^{-2}$ while in L-mode, it reaches only

$-(42 \pm 5)\mathrm{Vcm}^{-2}$. These values are typical of L-mode and H-mode discharges on ASDEX Upgrade [3, 4]. Around this region of negative shear, at $\rho_{pol} \approx 0.90$, an L_r of (0.37 ± 0.04)cm in H-mode and (0.88 ± 0.04)cm in L-mode was measured. As expected, the radial correlation length reduces with improved confinement and increasing $|\partial E_r/\partial r|$.

Of particular interest is the relationship between L_r and the turbulent wavenumber $k_\perp$. This can be examined with the correlation Doppler system since the tilted antennae of a Doppler reflectometer probe a non-zero turbulent wavenumber, $k_\perp$. The wavenumber is given by the Bragg equation: $k_\perp = 4\pi \sin\theta_{tilt}/\lambda_\circ$, where θ_{tilt} is the geometric tilt angle between the plasma flux surface normal and the incident microwave beam and $\lambda_\circ$ is the wavelength of the incident microwave. The antennae on ASDEX Upgrade are fixed so to vary the tilt angle and hence, $k_\perp$, the plasma shape is scanned from low to high triangularity. This was performed in two similar L-mode upper single null discharges (#19146 and #19148) and the results are shown in figure 3. Figure 3 shows L_r increasing with $k_\perp$. This is a surprising result since simple theory would argue that higher $k_\perp$ means smaller probed turbulent wavelengths $\Lambda_\perp$ which should coincide with smaller structure size and hence smaller radial correlation lengths.

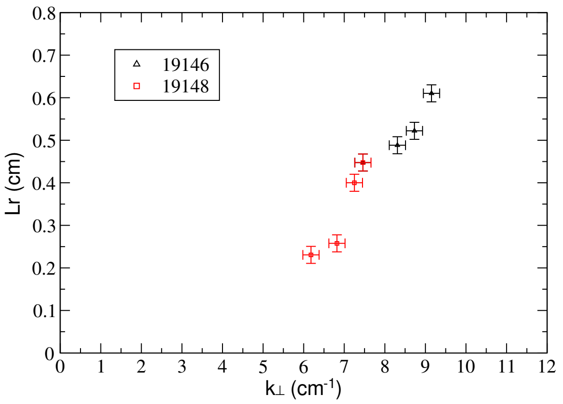
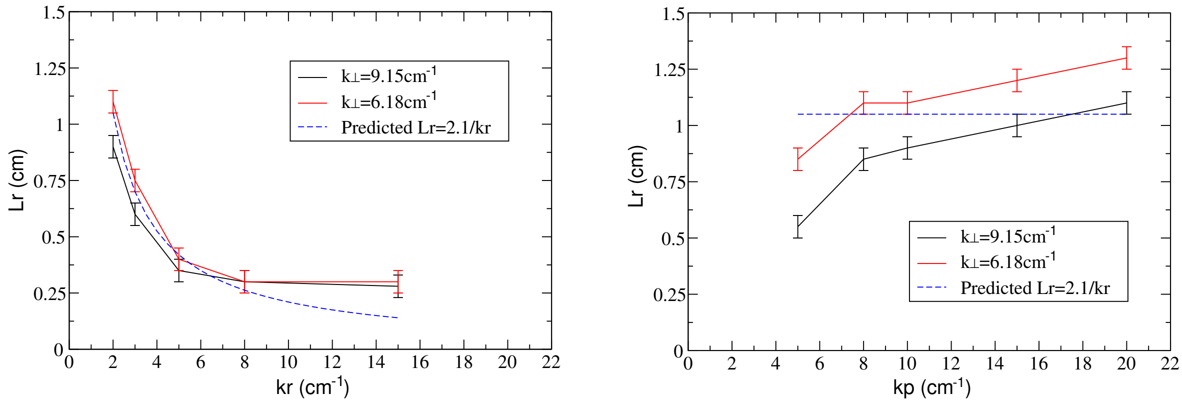


Figure 3: Radial correlation lengths as a function of $k_\perp$. The measurements were collected during a triangularity ramp in Upper Single Null L-mode discharges #19146 and #19148 using X-mode polarization.

Simulation Results In order to clarify the results shown in figure 3, a 2D full wave Finite Difference Time Domain code (FDTD) was utilized to simulate the Doppler reflectometer response [6]. The code solves Maxwell's equations for X-mode propagation in a plasma using a finite difference time-domain algorithm developed by Blaschak and Kriegsmann [7]. The experimental density, magnetic field and antenna characteristics are all included as input parameters. The turbulence is modelled using a Fourier summation with selectable radial and poloidal wavenumbers (i.e. k_r and k_p), satisfying the relationship $L_r = 2.1/k_r$, as described in reference [8]. The output of the code gives the In-phase I and Quadrature Q signals. The simulations were run for two cases ($k_\perp$=6.18cm^{-1} and 9.15cm^{-1}) corresponding to the two extreme points in figure 3. For each case, simulations were run for a set of 8 frequencies, ranging between 61.0GHz to 65.0GHz. By cross correlating the resultant I and Q signals, L_r could be obtained from the coherence curves. The results from the simulation are shown for a 2.5% fluctuation level in figure 4.

Figure 4(a) shows a scan in k_r. For both $k_\perp$ cases, the simulated correlation lengths agree with those predicted by the turbulence model (i.e. $L_r = 2.1/k_r$). This confirms that the diagnostic is capable of measuring L_r. Note that at higher k_r values, the simulated L_r starts to diverge from the predicted L_r, which has also been observed in experiment since the diagnostic can only measure an L_r larger than the width of the 1st Airy lobe. In this case, the limit is reached by $L_r \approx 0.25$cm. Figure 4(b) shows that L_r increases slightly with k_p. Although further runs need to be performed at different $k_\perp$ to further test this, this might offer an explanation as to why L_r in the experiment increases with $k_\perp$. It is also possible that during the triangularity



(a) k_r scan: 2.5% fluctuations, $k_p = 10cm^{-1}$

(b) k_p scan: 2.5% fluctuations, $k_r = 2cm^{-1}$

Figure 4: *The simulation results during a scan in k_r and k_p. The blue dashed curve/line represents the predicted radial correlation lengths.*

ramp the plasma turbulence was changing which may account for the unexpected trend in L_r shown in figure 3.

Summary The experimental results show a link between E_r, $\partial E_r/\partial r$ and L_r which agree with theory. The correlation Doppler reflectometer diagnostic may be used successfully for simultaneous measurements of these three quantities, opening the door for a wide variety of experiments and insight regarding plasma turbulence. During a triangularity ramp, L_r was observed to increase with $k_\perp$. The simulation results using a 2D FDTD code have illustrated that the diagnostic technique may be applied for L_r measurements. The main plausible explanation for the surprising relationship between L_r and $k_\perp$ may be that by changing the plasma shape, the nature of the edge turbulence was changed. To remove the shape dependence, the experiment will be repeated in the near future with tiltable antennae, allowing the measurement to be performed under constant plasma conditions.

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