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 $\Delta r$. 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 – 1.6s), L-mode ECRH heated (2.5 – 2.6s) and L-mode NBI heated
phases (6.3 – 6.4s) 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 reflectometry 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.

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 $-(290 \pm 30) \text{Vcm}^{-2}$ while in L-mode, it reaches only
\[ \frac{-(42 \pm 5)}{Vcm^{-2}}. \] 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 \((0.37 \pm 0.04)\)cm in H-mode and \((0.88 \pm 0.04)\)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:

\[ k_\perp = 4\pi \sin \theta_{tilt}/\lambda, \]

where \( \theta_{tilt} \) is the geometric tilt angle between the plasma flux surface normal and the incident microwave beam and \( \lambda \) 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.

**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 \( (k_\perp = 6.18cm^{-1} \text{ and } 9.15cm^{-1}) \) 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 \( L_r \approx 0.25cm \).

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...
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.

**References**