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Radial Electric Field Shear and Correlation Length Measurements in ASDEX Upgrade using Correlation Doppler Reflectometry

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Introduction The radial electric field shear (dE_r/dr) in H-mode is believed to be responsible for confinement improvement and reduction of anomalous transport [1]. This hypothesis can be investigated by correlating the level of density fluctuations and the magnitude of the radial correlation length of the turbulence (L_r) to the magnitude of the E_r shear. Previous measurements on several machines indicate that density fluctuations are reduced in the edge region after the L to H-mode transition [2,3,4,5]. On ASDEX Upgrade, a new diagnostic technique is being developed, called radial correlation Doppler reflectometry, which can measure both the radial electric field shear and the radial correlation length of the density turbulence. The diagnostic measures the perpendicular velocity $u_\perp$ from the Doppler frequency shift (induced by a tilted antenna) from which E_r is deduced. In addition to providing high spatial and temporal resolved E_r shear measurements, the diagnostic can also be used to study turbulent properties. The first results from this new diagnostic set-up are presented in this paper.

Technique The correlation Doppler reflectometry system, installed on ASDEX Upgrade, consists of two 50-74 GHz heterodyne reflectometers with steppable launch frequencies and selectable O or X-mode polarization [6]. For this study, the two reflectometer channels are connected to the same antenna pair by a combination of waveguide switches and directional couplers such that the reflectometers can be run either both in O or both in X mode configuration. Launching two microwave beams from the same tilted hog-horn antenna allows the measurement of E_r shear and L_r for a variety of plasma scenarios.

By repetitively sweeping the launch frequencies of the microwave beams with a constant fixed frequency difference, two simultaneous radial profiles of the perpendicular rotation velocity ($u_\perp$) can be constructed from the Doppler frequency shift in the reflectometer signal. The perpendicular rotation velocity is given by $u_\perp = f_D\ \lambda\ /\ 2\sin\theta$ where f_D is the doppler shift, λ is the wavelength of the incident microwave and θ is the geometric tilt angle between the plasma flux surface normal and the incident microwave beam. For evaluating the radial cutoff positions, the n_e profile needs to be known. The profile is provided by other diagnostics such as Thomson-scattering, swept frequency profile reflectometry and lithium beam. $u_\perp$ is also the sum of the $E \times B$ velocity, $v_{E\times B}$, and the intrinsic phase velocity of the turbulence, v_{ph}. In the edge region for drift wave turbulence, v_{ph} is negligible [7] and hence, the E_r profiles for each channel can be determined by the equation $E_r = -\ u_\perp \times B_{tot}$. The magnetic field measurements, B_{tot}, are provided by function parameterisation [8]. Finally, taking the difference between the two channels' E_r values measured at the same time divided by their radial separation gives a radial profile of the instantaneous E_r shear. The E_r shear measurements presented here are collected using a frequency sweep pattern of 1 GHz steps from 50 to 74 GHz in 100 ms with a fixed 2 GHz separation.

For radial correlation length measurements, on the other hand, the launch frequency of one channel, f_1, is held constant while the frequency of the other channel, f_2, sweeps in the vicinity of the first, allowing the reflectometers to probe different radial locations in the plasma as shown in Figure 1. The frequency pattern for the measurements presented here is a sweep every 50 ms with a frequency difference between the two channels starting at 0.1 GHz (to avoid any cross talk between the two channels) and increasing logarithmically.

Cross correlating the two Doppler shifted reflectometer signals gives the coherence between the two signals as a function of their frequency separation. Again, the n_e profile is required to translate the frequency separation to a radial separation $\triangle r$. The radial correlation length is then defined as the separation for which the coherence has decreased to 1/e. Previously there has been ambiguity over the type of reflectometer signals best used to determine radial correlation lengths as well as in how the L_r lengths are defined [9]. An advantage of the current heterodyne reflectometers is the ability to study how the correlation length depends on the various reflectometer signals correlated. The reflectometer signals tested in this study are the homodyne in-phase (I), homodyne quadrature (Q), amplitude, phase and complex (I+iQ) signals.

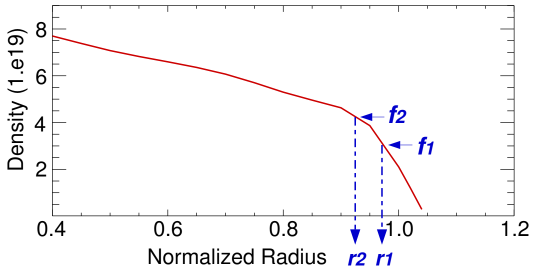
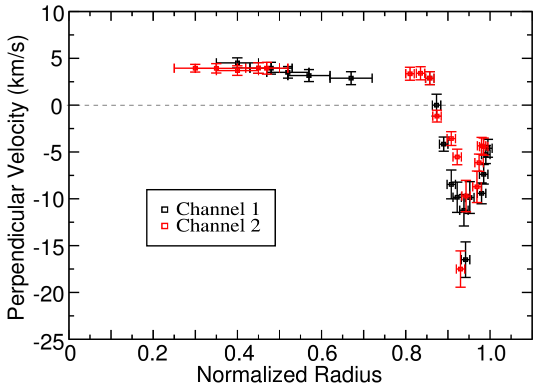
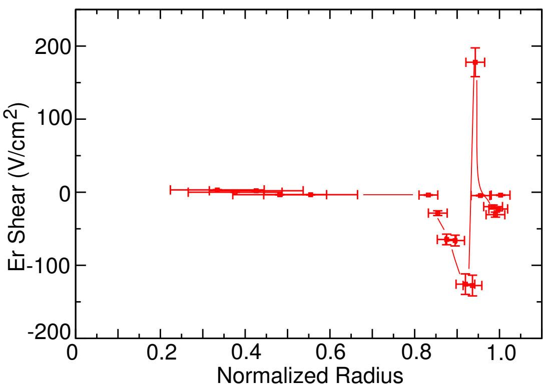


Figure 1: Density profile for an ELMy H-mode discharge (#17973, $t = 6.03\,s$).

Results Figure 2 shows an example E_r shear profile for an ELMy H-mode discharge. The $u_\perp$ profiles are first constructed as described above and are shown in Figure 2a for the two channels. For typical discharges in ASDEX Upgrade, the edge $u_\perp$ ranges from about 5-10 km/s in L-mode and 15-20 km/s in H-mode. The E_r profiles are then calculated together with dE_r/dr using the $u_\perp$ profiles. Note that the shear in Figure 2b is positive near the separatrix and large and negative (approximately -150 V/cm^2) a few cm within the plasma edge. The reversal in the sign of dE_r/dr can also be seen in Figure 2a where the plasma rotation changes from positive slope to negative slope heading inwards from the plasma edge.



(a) $u_\perp$ profiles

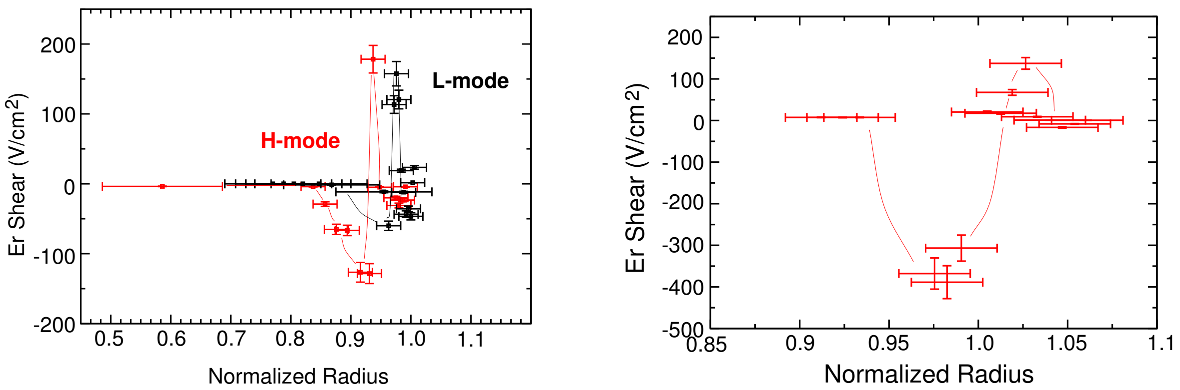


(b) E_r shear profile

Figure 2: $u_\perp$ profiles for two reflectometer channels from which the dE_r/dr is extracted for an H-mode discharge (#17973). The data was collected with both reflectometers in O-mode configuration.

In comparing the shear measured in L-mode and H-mode as seen in Figure 3a, three observations can be made. First, the shear is localized at the plasma edge and zero elsewhere. Second, the H-mode E_r shear profile is shifted inwards in comparison to the L-mode profile. This may be due to the density pedestal which steepens and moves inwards during an

H-mode [10]. The third observation is that the absolute value of the edge E_r shear increases after the L-H transition. Typically at ASDEX Upgrade the maximum negative edge E_r shear measured in L-modes is between 0 and -75 V/cm^2 and in H-modes between -150 and -250 V/cm^2. This enhanced shear in H-mode is observed for all types of H-modes, i.e. NBI heated, ICRH, etc. Biglari, Diamond and Terry (BDT model) [11] predict that an increase in absolute shear suppresses density fluctuations and stabilizes the turbulence. The data shown in Figure 3 is consistent with their model. Figure 3b shows the shear measured on ASDEX Upgrade during a Quiescent H-mode phase [12,13]. The QH phase, like the ELMy H-mode has very high confinement but is ELM-free. In ASDEX Upgrade the highest shear measured to date has been during the QH phase. It has been suggested by Burrell [14] that this strong shear (greater than -400 V/cm^2) in this plasma regime may be an explanation for the observed ELM stabilization.



(a) L-mode (#18103) versus H-mode (#17973)

(b) Quiescent H-mode (#18925)

Figure 3: *dE_r/dr profiles showing enhanced edge shear in H and QH-modes. Note the different scale.*

To see how dE_r/dr measurements relate with turbulent properties, radial correlation lengths were also measured with the Doppler correlation reflectometer system. First, a study to determine the performance of the various reflectometer signals in obtaining radial correlation lengths was performed. The results are shown in Figure 4 for an L-mode discharge at $\rho_{pol} \approx 0.98$. The coherence was obtained by correlating the homodyne I ($A\cos\phi$) and Q ($A\sin\phi$) signals as well as amplitude (A), phase (ϕ) and complex signals ($Ae^{i\phi}$). For all L_r measurements on ASDEX Upgrade, the complex and homodyne signals consistently give larger L_r than the amplitude and phase signals as shown in Figure 4. Estrada also investigated this subject and found that the homodyne signals performed more reliably than the amplitude and phase signals [15]. This is most likely due to the fact that the homodyne and complex signals include both amplitude and phase information and

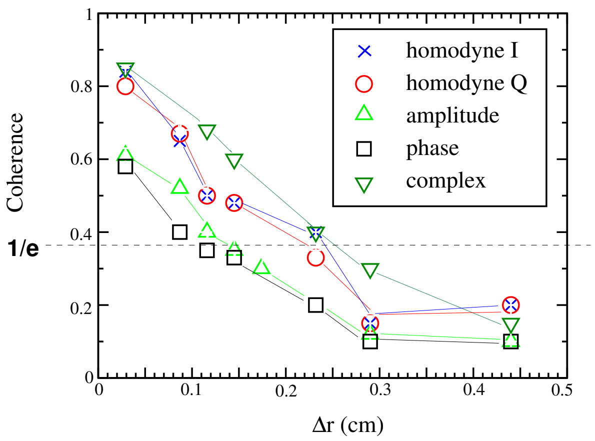


Figure 4: *Coherence profiles measured during an L-mode discharge (#18761, $k_\perp = 9.56 - 10.2\ cm^{-1}$).*

therefore do not assign too much weight to either parameter, particularly during periods of low reflected power.

Figure 5 shows the complex coherence measured in an H-mode at $\rho_{pol} \approx 0.98$. Taking the distance over which the coherence has dropped to 1/e, a correlation length of 0.09 cm is obtained. Comparing this with the correlation length obtained in Figure 4 for L-mode (0.24cm), it is noted that the correlation length decreases to at least half its value after the L-H transition. Doppler reflectometry offers an additional level of information, since changing the tilt angle of the antennas introduces a non-zero turbulent wavenumber, $k_\perp$. (Normal incident reflectometry measures L_r for $k_\perp = 0$). Measurements are in progress to determine the relationship between L_r and $k_\perp$. Nevertheless, the enhanced edge shear measured in H-mode is correlated to a reduction in L_r, consistent with the hypothesis that sheared flow distorts turbulent eddies and leads to a decorrelation of the density and velocity perturbations.

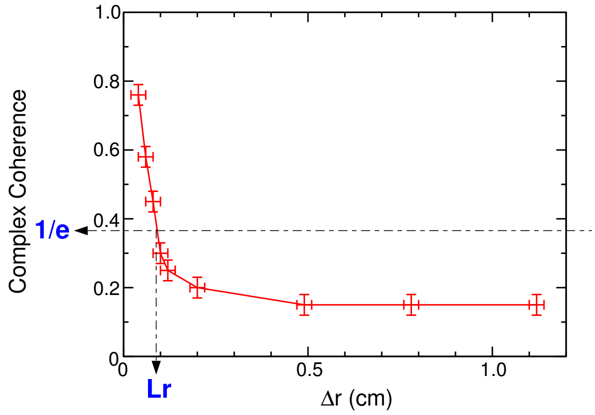


Figure 5: *Complex coherence measured during an H-mode discharge (#18749, $k_\perp = 6.6 - 7.1$ cm^{-1}).*

Summary In conclusion, using the new Doppler correlation reflectometer system on ASDEX Upgrade successful measurements of dE_r/dr and L_r have been made in various plasma scenarios. The edge E_r shear measurements show an increase in absolute value in H-modes and QH-modes. Positive E_r shear is observed outside the separatrix in all cases. The relationship between the E_r shear and L_r has also been examined and an enhanced shear can be correlated to a decrease in the turbulent fluctuation property, L_r. The L_r measured in L-modes are roughly between 0.2 to 0.4 cm and about 0.1 cm in H-mode at $\rho_{pol} \approx 0.98$.

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