Measurement of Correlation Lengths by Reflectometry in the Edge Plasma of ASDEX Upgrade

B. Kurzan, M. Maraschek, W. Schneider, J. Schweinzer, B. Scott, F. Serra*, W. Suttrop, A. Zeiler, ASDEX Upgrade Team

Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-85748 Garching, Germany

**Centro de Fusão Nuclear, EURATOM-Association, Instituto Superior Técnico, 1096 Lisboa Codex, Portugal*

1) Introduction

Measuring correlation lengths in the plasma edge region is a means to test theories calculating the properties of the plasma turbulence and the resulting transport. The correlation lengths which are important for the radial transport and thus the plasma confinement are perpendicular to the magnetic field either in the poloidal, or radial direction. The measuring technique and the scaling of the radial correlation lengths compared to current turbulence theories will be presented in this paper.

2) Diagnostic

The technique used here to measure the radial correlation lengths is correlation reflectometry: Two simultaneously acquired signals are correlated, one at a fixed, another at a varying position [1]. The ASDEX Upgrade reflectometry system [2] features one frequency per antenna which can be swept very fast, typically in $100\ \mu\mathrm{s}$, over the whole available frequency band. Two signals reflected at slightly different times from two different cut-off-layers can be correlated quasi-simultaneously, if the time for shifting the microwave frequency over a turbulent structure is smaller than its lifetime which is about $20\ \mu\mathrm{s}$ as estimated from mixing length theory. Typical radial correlation lengths are of the order of some millimeters which is a fraction of the spatial range covered by a complete frequency sweep. The time needed for crossing such a turbulent structure is much smaller than the full sweeping time of $100\ \mu\mathrm{s}$. Thus the condition for quasi-simultaneous probing is fulfilled for the reflectometry system used.

3) Determination of the Correlation Lengths

The correlation coefficient between two raw signals $\mathrm{U}_{1\mathrm{i}}$, $\mathrm{U}_{2\mathrm{i}}$ of reflectometry, $\mathrm{U}_{1\mathrm{i}} = \mathrm{A}_1 \cos(\varphi_{1\mathrm{i}})$ and $\mathrm{U}_{2\mathrm{i}} = \mathrm{A}_2 \cos(\varphi_{2\mathrm{i}})$ [A_1, A_2: amplitudes and $\varphi_{1\mathrm{i}}$, $\varphi_{2\mathrm{i}}$: phases of the reflected waves for the two positions 1 and 2] is

$$\mathrm{C} \propto \mathrm{A}_1 \mathrm{A}_2 \left\{ < \cos\left(2\tilde{\varphi}_{\mathrm{i}}\right) > \left[\cos^2(\varphi) - \sin^2(\Delta\varphi)\right] - < \cos\left(\varphi_{1\mathrm{i}}\right)\cos\left(\varphi_{2\mathrm{i}}\right) > \right\}$$

[$< \mathrm{x_i} > = \left(\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{x_i}\right)/\mathrm{N}$, N: number of consecutive sweeps, typically $\mathrm{N} = 16$, $\varphi = < \varphi_{1\mathrm{i}} + \varphi_{2\mathrm{i}} > /2$, $\Delta\varphi = < \varphi_{2\mathrm{i}} - \varphi_{1\mathrm{i}} > /2$, $\tilde{\varphi}_{\mathrm{i}} = (\varphi_{1\mathrm{i}} + \varphi_{2\mathrm{i}})/2 - \varphi$]. This describes an interference pattern modulated by $< \cos(2\tilde{\varphi}_{\mathrm{i}}) >$, the wanted correlation function. The reference position is chosen such that $< \cos(\varphi_{1\mathrm{i}}) > = 0$ so that only the interference pattern modulated by the spatial correlation is observed and evaluated. When plotting C versus the spatial distance between the nominal cut-off layers of the two signals phase jumps are obtained, making it difficult to determine the spatial evolution of the correlation. Plotting C^2 eliminates this problem (fig. 1). The correlation length $\Delta\mathrm{R} = \mathrm{l_C}$ is reached when $\mathrm{C}^2 = 1/\mathrm{e}$.

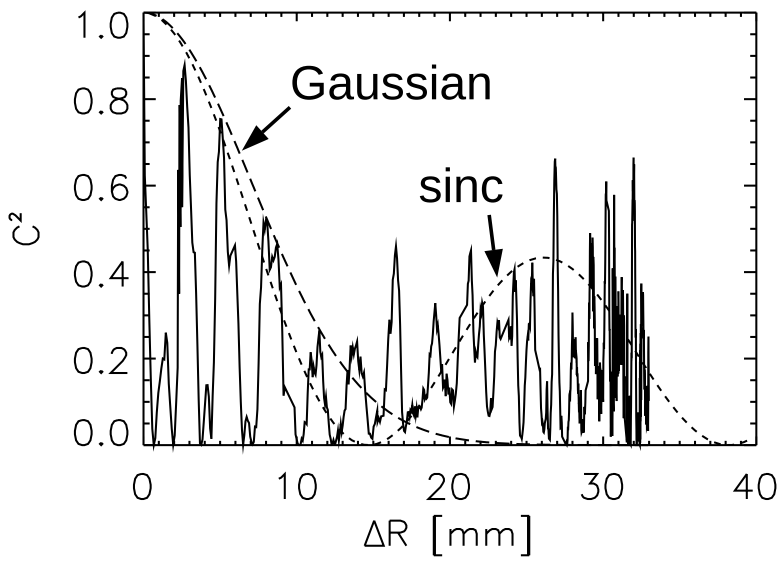

Fig. 1: Correlation C^2 versus distance $\Delta\mathrm{R}$ between the cut-off layers (solid line) approximated by a Gaussian curve (broken line) and sinc- functions (dotted line).

For a Gaussian wavevector spectrum of the probed turbulence a monotonously decreasing correlation coefficient is expected when increasing $\Delta\mathrm{R}$ (see fig. 1). This, however, is not observed, but the correlation coefficient shows a second maximum for $\Delta\mathrm{R} \neq 0$. This behavior can be approximated by two sinc functions (see fig. 1) equivalent to an observed wavevector range $0 \leq \mathrm{k} \leq 0.2\,\mathrm{k_0}$ of finite width with $\mathrm{k_0}$ as the microwave's wavevector in vacuum. The microwave radiation can undergo Bragg scattering along its path inside the plasma for the matching wavevector range $0 \leq \mathrm{k} \leq 2\,\mathrm{k_0}$ where the resonance with $\mathrm{k} \approx 0$ is located very near to the cut-off layer and $\mathrm{k} \approx 2\mathrm{k_0}$ is fulfilled near the plasma boundary to vacuum. From the experimentally obtained wavevector range it follows that the observed signals are dominated by Bragg scattering near the cut-off layer. Thus the correlation measurement is well localized.

4) Radial Profile of the Correlation lengths

The radial profiles of the measured correlation lengths show different structures depending on the frequency range of the analyzed turbulence (fig. 2): For the frequencies $1 - 200\,\mathrm{kHz}$ $\mathrm{l_C}$ reaches values of some centimeters inside and outside the separatrix. In Ohmic plasmas $\mathrm{l_C}$ has a maximum of some centimeters on the $\mathrm{q} = 4$ flux surface. The location of the q-surfaces is deduced via the reconstruction of the plasma equilibrium from magnetic measurements. Filtering the signals in the frequency range $50 - 200\,\mathrm{kHz}$ results in reduced correlation lengths at the rational q-surfaces. Thus the big correlation lengths are due to modes in the frequency range $1 - 50\,\mathrm{kHz}$ and are ascribed to the presence of MHD modes.

A dip in the correlation length profile with a width of about 2 – 3 cm is observed around the separatrix (fig. 2). This effect can already be explained by a small poloidal rotation of the

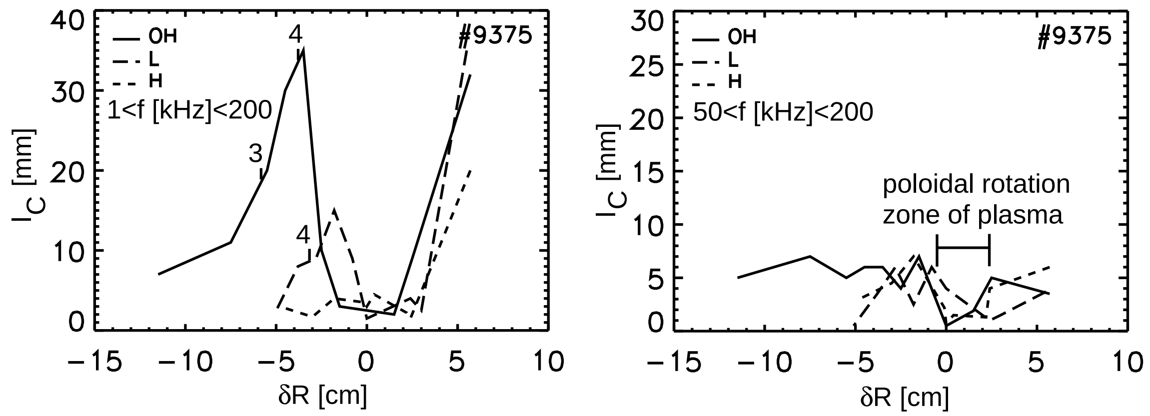

Fig. 2: Radial profiles of the measured correlation length l_C *versus its relative position* δR *to the separatrix, where* $\delta R > 0$ *is outside the separatrix. The correlation lengths are shown here for different frequency ranges of the observed turbulence,* $1 - 200\,\mathrm{kHz}$ *and* $50 - 200\,\mathrm{kHz}$*, and confinement regimes (Ohmic, L, and H mode).*

plasma by which poloidally separated and uncorrelated regions enter the line of sight of the reflectometer during the sweeping time, resulting in a reduced apparent correlation length. The poloidal velocity necessary for this effect is $v_{Pm} = l_p/\Delta t$ [l_P: poloidal correlation length, Δt: time interval during which the two signals to be correlated are acquired]. The poloidal velocity resulting for $l_P = 1\,\mathrm{cm}$ [3] and $\Delta t = 10\,\mu s$, $v_{Pm} = 10^3\,\mathrm{ms}^{-1}$, is much smaller than the typical diamagnetic poloidal plasma velocity $v_{Pd} = 4 \times 10^3\,\mathrm{ms}^{-1}$. Thus the apparent decorrelation observed here near the separatrix is already explained by the poloidal rotation of the plasma and it cannot be concluded that an $\vec{E} \times \vec{B}$ shear is causing this.

The measured correlation length l_C is not influenced by the toroidal rotation of the plasma, if its velocity $v_T \lessapprox l_T/\Delta t$ [l_T: toroidal correlation length]. The boundary for the toroidal velocity resulting for a typical measured value of $l_T = 0.2\,\mathrm{m}$ in $v_T \lessapprox 20\,\mathrm{km/s}$ compares with the toroidal plasma velocity at the plasma edge, $v_T = (20 \pm 20)\,\mathrm{km/s}$, measured by charge exchange spectroscopy. Thus only inside, but very near to the separatrix the measured correlation length l_C is unperturbed by the small local toroidal and poloidal plasma rotations and equals the radial correlation length l_R of the turbulence inside the moving plasma.

5) Scaling of the Radial Correlation Length

The experimental data presented here were obtained $2\,\mathrm{cm}$ inside the separatrix for deuterium plasmas with deuterium neutral beam injection heating covering the parameter range $2.6 \times 10^{19}\,\mathrm{m}^{-3} < n_e < 5.9 \times 10^{19}\,\mathrm{m}^{-3}$ (electron density), $1.51\mathrm{T} < B < 2.96\mathrm{T}$ (magnetic field), $3.0 < q_a < 5.81$ (edge safety factor), and $40\mathrm{eV} < T_e < 520\mathrm{eV}$ (electron temperature). When plotting the radial correlation length l_R normalized to the effective gyroradius $\rho_S = c_S/\Omega_i$ [$c_S = \sqrt{2kT_e/M_i}$, $\Omega_i = eB/M_i$, k: Boltzmann constant, M_i: ion mass, e: elementary charge] versus ρ_S (fig. 3) it is seen that for $\rho_S > 1.3\,\mathrm{mm}$ the ratio l_R/ρ_S is about 2 and constant. This means that for warmer L and H mode plasmas the radial correlation length is proportional to the effective gyroradius. This is expected for η_i driven turbulence [4]. For $\rho_S < 1.3\,\mathrm{mm}$ the radial correlation length is decreasing with increasing

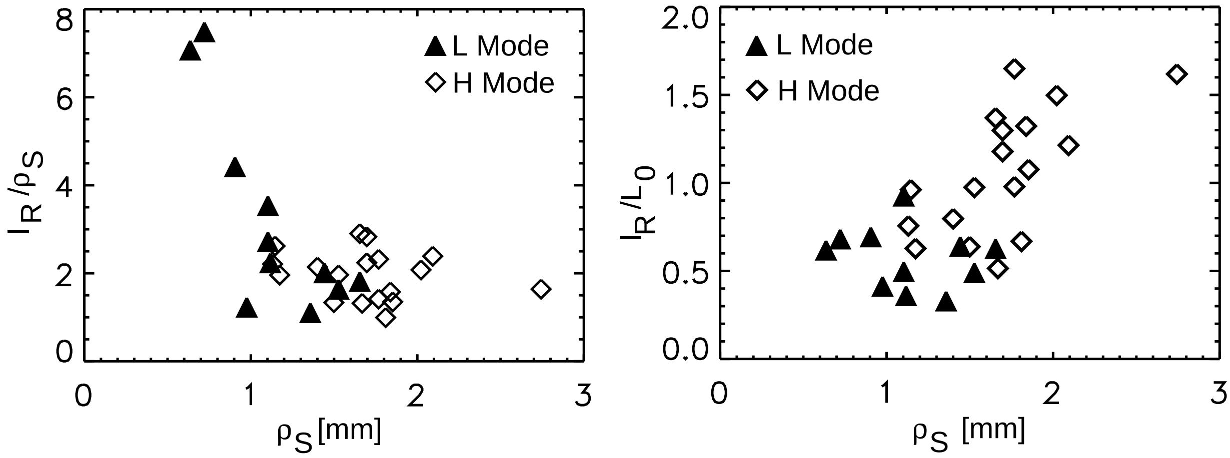

Fig. 3: Scaling of the radial correlation length l_R normalized to the effective gyroradius ρ_S and normalized to L_0 versus ρ_S.

ρ_S. Here the Resistive Ballooning turbulence [5] is dominant and l_R scales much better with its intrinsic turbulence cell size

$$L_0 = 2\pi q_a \left(\frac{\nu_{ei} R \rho_S}{2\Omega_e}\right)^{1/2} \left(\frac{2R}{L_n}\right)^{1/4}$$

[ν_{ei}: electron-ion collision frequency, R: major plasma radius, Ω_e: electron cyclotron frequency, L_n: scale length of electron density profile] (fig. 3). Here for $\rho_S < 1.3\,\mathrm{mm}$ a constant ratio of $l_R/L_0 \approx 0.7$ is measured.

6) Summary and Conclusion

It was shown that radial correlation lengths can be measured by a fast sweeping single frequency reflectometry system, as long as the time needed to sweep the microwave frequency over the turbulent structure is smaller than its lifetime. In this case two radial positions can be correlated quasi-simultaneously. For warmer L and H mode plasmas the radial correlation length is proportional to the effective gyroradius, as expected for η_i driven turbulence. For cold L mode plasmas the radial correlation length scales according to the turbulence cell size of the Resistive Ballooning turbulence.

References

[1] G. R. Hanson, et al., Rev. Sci. Instrum. 61, 3049 (1990); T. L. Rhodes, et al., Rev. Sci. Instrum. 63, 4661 (1992); J. Sanchez, et al., Rev. Sci. Instrum. 64, 487 (1993); E. Mazzucato, et al. Phys. Rev. Lett. 71, 1840 (1993); A. E. Costley, et al., JET report JET-P(93)102; T. L. Rhodes, Rev. Sci. Instrum. 66, 824 (1995)
[2] A. Silva, et al., Rev. Sci. Instrum. 67(12), 4138 (1996)
[3] Ch. P. Ritz, et al., Phys. Rev. Lett. 65, 2543 (1990)
[4] A. Zeiler, et al., Phys. Plasmas, in press
[5] A. Zeiler, et al. Phys. Plasmas 3(8), 2951 (1996); A. Zeiler, et al., Phys. Plasmas 4(4), 991 (1997)