# Radial correlation Doppler reflectometry in the TJ-II stellarator: Measurements and two-dimensional full-wave simulations

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**Abstract.**

Radial correlation Doppler reflectometry is studied with a 2D full-wave code and the TJ-II Doppler reflectometer system [1]. The numerical results show that in most cases the radial correlation length $L_r$ measured by reflectometry is different from the turbulence radial correlation length. However Doppler reflectometry can estimate $L_r$ if the probing beam angle is properly chosen and the measurements are performed in linear regime [2]. In non-linear regime $L_r$ is underestimated. First measurements carried out in TJ-II using Doppler reflectometry are presented. Broad scans in the probing beam angle have been performed. The comparison between the numerical results and the experimental ones indicates that both linear and non-linear regimes have been found. Based on the simulation results an experimental procedure is applied to determine the turbulence radial correlation length.

## I. Introduction

Recently, the linear theory of radial correlation Doppler reflectometry has been developed with very promising results [3]. Due to the finite antenna tilt angle angle used in Doppler reflectometry, this technique should not be sensitive to the forward scattering dominant component of conventional reflectometry providing better estimations of the turbulence radial correlation length in linear regime. In this work, we perform a 2D full-wave study of both conventional and Doppler correlation reflectometry in a wide range of antenna tilt angles. Both linear and non-linear regimes are considered [4]. In addition, first measurements carried out using radial correlation Doppler reflectometry in the TJ-II stellarator are presented.

## II. Numerical results

Figure 1 shows the coherence $\gamma$ between the two reflectometry channels as a function of the radial separation between them for different antenna tilt angles ($\theta$ = 0º - 50º). The radial cross-correlation function of density fluctuations is shown by the solid black line. The radial correlation length is $L_r$ = 7.5 mm and the turbulence level is $\delta n_{rms} / n_c$ = 1% (fig. 1a) and $\delta n_{rms} / n_c$ = 15% (fig. 1b). Figure 1a shows that $L_r$ decreases as $\theta$ increases. At low antenna tilt angles Doppler reflectometry overestimates $L_r$. The results show that $L_r$ does not converge to the true value when the antenna tilt angle increases. The figure shows that there exists an optimum antenna tilt angle to estimate this particular radial correlation length ($\theta \approx$ 25º). As shown in [2] such an optimum antenna tilt angle can be found experimentally. At high turbulence levels (fig. 1b) there is no optimum antenna tilt angle. $L_r$ is underestimated whatever the antenna tilt angle is. Furthermore, the estimated radial correlation length becomes nearly independent of the antenna tilt angle. This may help the experimentalists to distinguish between linear and non-linear regime.

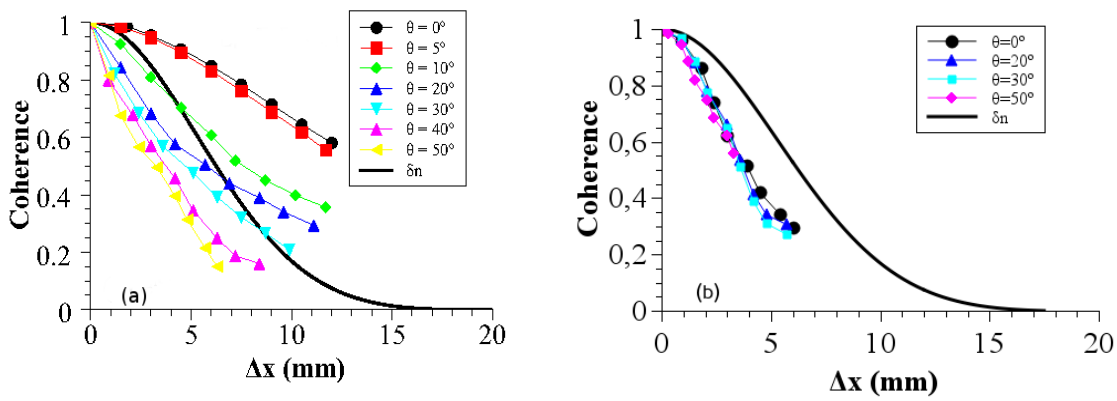


Figure 1. Coherence γ between the two reflectometry channels as a function of the radial separation between them. The turbulence radial correlation length is Lr = 7.5 mm. The radial cross-correlation function of density fluctuations is shown by the solid black line. The turbulence level is $\delta n_{rms}/n_c = 1\%$ (a) and $\delta n_{rms}/n_c = 15\%$ (b).

## III. Measurements in the TJ-II stellarator

Low-density ($\langle n_e \rangle = 0.55 \times 10^{19}$ m$^{-3}$) and pure ECH-heated plasmas ($P_{ECH}$ = 500 kW) in the standard magnetic configuration (rotational transform at the plasma edge $\iota_a = 1.63$) were chosen to obtain easily reproducible discharges with steady conditions for a long enough time period. The antenna tilt angle was changed in a shot-to-shot basis. The experimental results are shown in figure 2. The coherence is plotted as a function of the radial separation between the two reflectometry channels for different probing beam angles and two different plasma regions: an inner one (ρ ≈ 0.65, figure 4, left) and the outer one (ρ ≈ 0.75, figure 4, right). A marked difference can be observed when comparing both figures. In the inner region, data analysis provides a relatively large $L_r \approx 2.2$ cm, for small probing beam angles. This value decreases when the probing beam angle increases reaching values as short as 0.3 cm (smaller than the probing wavelength). On the contrary, in the outer region, short radial correlation lengths are measured whatever the probing beam angle. The correlation length measured at small probing beam angles is $L_r \approx 0.6$ cm and decreases up to $L_r \approx 0.3$ cm for the largest probing beam angle. The comparison between the experimental data and the simulation results allows us to conclude that measurements carried out in the inner and in the outer positions correspond likely to linear and non-linear regimes, respectively [2, 5].

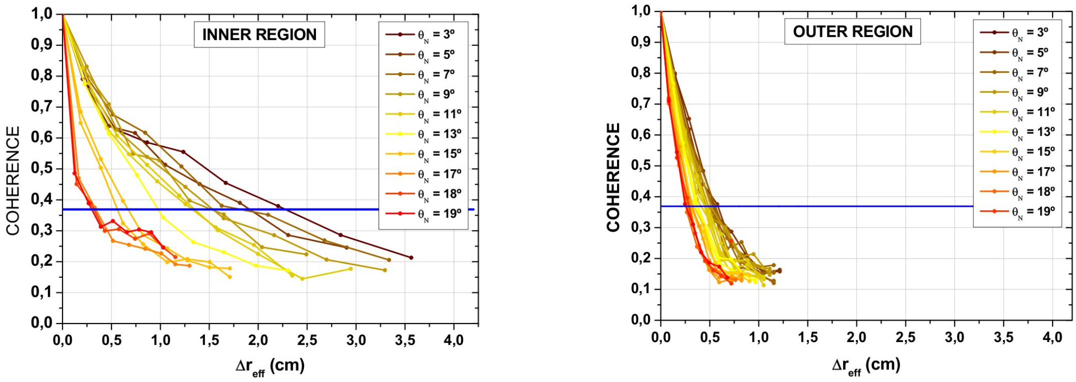


Figure 2. Coherence as a function of the radial separation between the two reflectometry channels measured at different probing angles in the inner plasma region (left) and in the outer one (right). The horizontal blue line represents the 1/e drop of the coherence that defines the radial correlation length.

The application of the procedure found in our previous simulations [2] (valid only for linear regime) to calculate the probing beam angle at which Doppler reflectometry gives the best estimation for the turbulence correlation length is shown in figure 3. The estimated radial correlation length is Lr ≈ 1.5 cm measured with a probing beam angle θ ≈ 15°.

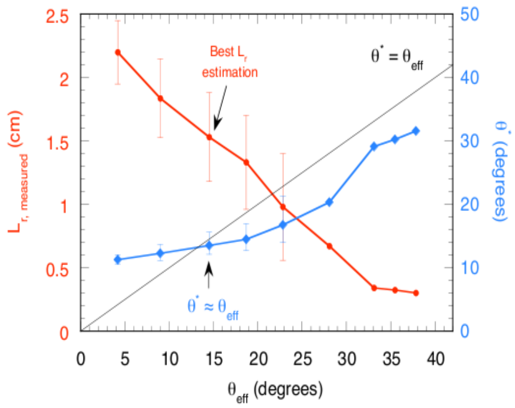


Figure 3. Radial correlation length (in red) obtained during the probing beam angle scan measurements taken at the inner plasma region. The optimum probing beam angle calculated for each case is also shown ($\theta^*$, in blue). The arrows indicate the case at which $\theta^* \approx \theta_{eff}$ and the corresponding radial correlation length.

Additional experiments were carried out in ECH-heated plasmas with $P_{ECH}$ = 500 kW with different plasma densities ($\langle n_e \rangle = 0.5 \times 10^{19}$ m$^{-3}$ and $\langle n_e \rangle = 0.3 \times 10^{19}$ m$^{-3}$) and changing slightly the magnetic configuration ($\iota_a$ = 1.59) with $P_{ECH}$ = 500 kW and $\langle n_e \rangle = 0.55 \times 10^{19}$ m$^{-3}$. As before, a continuous decrease in $L_r$ is found as the probing beam angle increases. No clear trends are found when considering possible dependences of $L_r$ on the plasma radius or plasma density. The most clear dependence is found when representing $L_r$ as a function of the density gradient scale length $L_N$. This dependence is shown in figure 4 for two data sets measured with $P_{ECH}$ = 300 kW (green) and at $P_{ECH}$ = 500 kW (blue). The turbulence radial correlation length decreases as the density gradient scale length decreases, being shorter at higher ECH heating power.

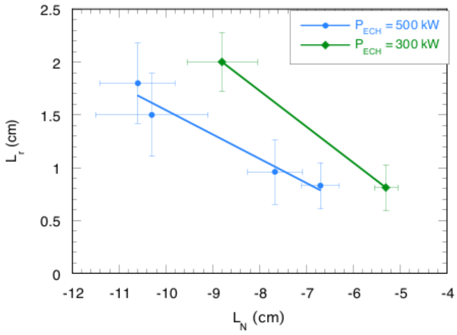


Figure 8. Best estimation of the radial correlation length as measured at the probing beam angles that verify $\theta^* = \theta_{eff}$ as a function of the density gradient scale length.

## IV. Conclusions

In linear regime Doppler reflectometry can be used to estimate the turbulence radial correlation length if the antenna tilt angle is properly chosen. At low antenna tilt angles $L_r$ is overestimated. The numerical results and the experiments performed in TJ-II show that $L_r$ decreases as the antenna tilt angle increases as expected from linear theory. Unfortunately if the antenna tilt angle is too large $L_r$ can be underestimated. The comparison with the numerical results indicates that both linear and nonlinear regimes have been found in the experiments. In the outer region ($\rho \approx 0.75$) correlation lengths shorter than the probing wavelength are measured at any probing beam angle, what suggests that measurements were performed in the non-linear regime. At inner plasma radius a pronounced dependence (characteristic of linear regime) of the correlation length on the probing beam angle is found; relatively long correlation lengths are measured at small probing beam angles decreasing gradually as the probing beam angle increases. Based on the simulation results an experimental procedure is applied to determine the turbulence radial correlation length.

## Acknowledgements

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