Measurement of Radial Correlation Lengths of Electron Density Fluctuations in Heliotron J Using O-Mode Reflectometry

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The radial correlation length L_r of electron density fluctuations has been measured using a two-channel O-mode reflectometer system in the helical-axis fusion plasma experimental device Heliotron J. The experimental results show that L_r is around 1.4 ± 0.7 mm in three different magnetic field bumpiness configurations (i.e. low, medium and high) for the low-density electron cyclotron heating (ECH) discharges. In high-density neutral beam injection (NBI) discharges with HIGP and pellet injection, L_r is found to be around 1 ± 0.2 mm.

Keywords: O-mode reflectometry, radial correlation length, electron density fluctuation, Heliotron J, turbulent transport

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Turbulence in magnetic confinement nuclear fusion reactors is believed to be the dominant driver of radial heat and particle transport in neoclassically optimized toroidal devices such as tokamaks and stellarators/heliotrons. For better particle/energy confinement and reactor control, the structure and transient behavior of turbulence should be understood and possibly mitigated. It is known that electron density fluctuations $\tilde{n}_e$ correlate up to a certain radial correlation length L_r, such that L_r could be an indication of the spatial size of a turbulent eddy. In a series of Doppler reflectometry experiments performed by Fernández-Marina *et al.* [1] in the TJ-II stellarator, L_r was found to be of the order millimeters to centimeters in low-density ECH plasmas ($\bar{n}_e = 0.55 \times 10^{19}\,\mathrm{m}^{-3}$). For the ASDEX Upgrade tokamak, Schirmer *et al.* [2] reported that L_r was 8.8 ± 0.4 mm in a high-density ECH plasma ($\bar{n}_e = 3.6 \times 10^{19}\,\mathrm{m}^{-3}$). In this paper, we report the first measurements of the radial correlation length L_r of electron density fluctuations $\tilde{n}_e$ in low-density ECH and high-density NBI plasmas in Heliotron J using a two-channel O-mode reflectometer system.

Heliotron J is a medium-sized helical-axis stellarator/heliotron device. The device parameters are outlined by Wakatani *et al.* [3] and Obiki *et al.* [4]. The two-channel O-mode reflectometer system used in Heliotron J comprises one scannable-frequency and one fixed-frequency reflectometer (both operating in the Ka-band with 26.5 - 40 GHz microwaves) with an IQ detection system that gives amplitude signals $A_{1,2}(t)$ of the electron density fluctuations [5]. Blanco and Estrada [6] discussed that correlation measurements of the amplitude signals $A_{1,2}(t)$ can provide a radial correlation length L_r close to the true turbulence radial correlation length. In this paper, we define L_r as the average effective distance $\Delta r_{eff} = r_2$ - r_1 for which the cross-correlation between $A_1(t)$ and $A_2(t)$ reaches $1/e$, where r_1 is held fixed and r_2 is varied by scanning the carrier frequency on a shot-to-shot basis, keeping the plasma parameters and magnetic configuration fixed.

Figure 1 shows the time-evolution of the basic plasma parameters in a low-density ECH discharge in three different bumpiness configurations. The diagnostic time-window for the correlation measurements is chosen at the peak-density of the discharge, from t = 250 - 260 ms. To filter system noise, a bandpass filter (5 KHz to 200 KHz) is applied to amplitude signals $A_{1,2}(t)$. No MHD modes were observed. Reflectometer measuring data with an overall low signal-to-noise ratio is not taken into account in this experiment.

For a series of low-density ECH discharges ($\bar{n}_e = 1.0 \times 10^{19}\,\mathrm{m}^{-3}$) in three different magnetic field bumpiness configurations (i.e. low, medium and high), the cross-correlation between $A_1(t)$ and $A_2(t)$ as a function of Δr_{eff} is depicted in Fig. 2. The used scanning range is 26.32 - 30.48 GHz, equivalent to cut-off densities 0.86×10^{19} -

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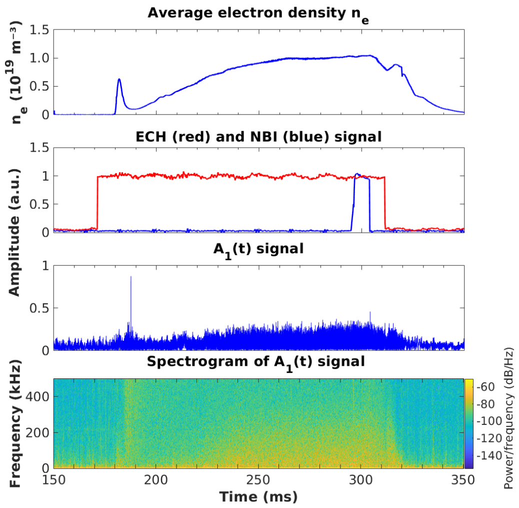

Fig. 1 Time evolution of the average electron density $\bar{n}_e(t)$, ECH and NBI signals (a.u.), electron density fluctuation amplitude signals $A_1(t)$ as measured by the two-channel O-mode reflectometer system and the spectrogram of $A_1(t)$ in an ECH discharge (#76025).

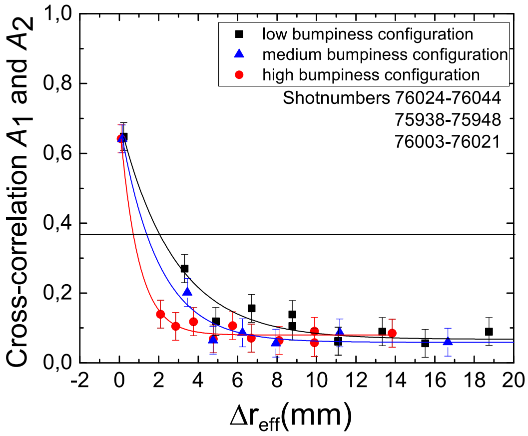

Fig. 2 Cross-correlation between the amplitudes of electron density fluctuations $A_1(t)$ and $A_2(t)$ as a function of the effective distance between the cut-off layers Δr_{eff} as measured in low-density ($\bar{n}_e = 1.0 \times 10^{19}\,\mathrm{m}^{-3}$) ECH discharges with three different magnetic field bumpiness configurations (i.e. low, medium and high). Exponential fitting functions are used.

$1.19 \times 10^{19}\,\mathrm{m}^{-3}$. The lowest frequency and cut-off density correspond to the fixed-frequency reflectometer. The cut-off radii $\rho_{1,2}$ are calculated using an electron density profile $n_e(\rho)$ obtained with a Thomson scattering diagnostic, with $\rho = r/a$ the normalized minor radius. For the used scanning range of frequencies, $\rho = 0.67$ - 0.91, which is converted to the minor radius r[mm] via $r = \rho a$, with a[mm] the position of the last closed magnetic flux surface. The same approach was used in a series of high-density NBI discharges ($\bar{n}_e = 3.0 \times 10^{19}\,\mathrm{m}^{-3}$) with High Intensity Gas Puffing (HIGP) and pellet injection in the medium bumpiness configuration, resulting in Fig. 3 (used carrier frequency scanning range: 26.32 - 34.29 GHz, cut-off density 0.86×10^{19} - $1.46 \times 10^{19}\,\mathrm{m}^{-3}$, $\rho = 0.70$ - 0.88). Due to a steep density profile, the cut-off positions are located at the edge regions in both the ECH and NBI plasmas. The $1/e$

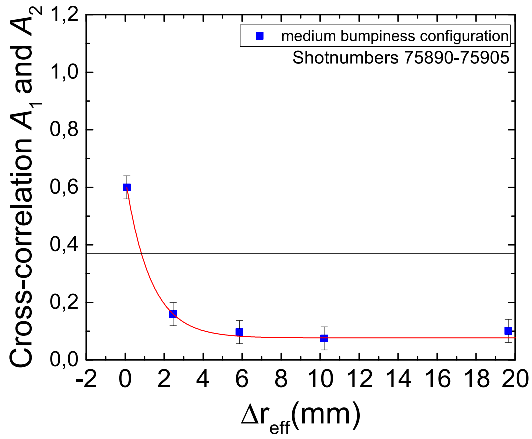

Fig. 3 Cross-correlation between the amplitudes of electron density fluctuations $A_1(t)$ and $A_2(t)$ as a function of the effective distance between the cut-off layers Δr_{eff} as measured in a high-density ($\bar{n}_e = 3.0 \times 10^{19}\,\mathrm{m}^{-3}$) NBI discharge with HIGP and pellet injection with medium bumpiness configuration. An exponential fitting function is used.

cross-correlation level is represented by a black horizontal line in both figures.

The experimental results show that L_r is around 1.4 ± 0.7 mm in three different magnetic field bumpiness configurations (i.e. low, medium and high) for the low-density ECH discharges. In high-density NBI discharges with HIGP and pellet injection, L_r is found to be around 1 ± 0.2 mm. For comparison: the ion Larmor radius $\rho_i \approx 2$ - 3 mm. As a future outlook, more data should be taken at the range of $\Delta r_{eff} < 2$ mm for a more accurate estimation of L_r. Furthermore, L_r could be explored in improved confinement discharges to check whether a relation between confinement and turbulence exists.

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[1] F. Fernández-Marina *et al.*, Nucl. Fusion **54**, 072001 (2014).
[2] J. Schirmer *et al.*, Plasma Phys. Control. Fusion **49**, 1019 (2007).
[3] M. Wakatani *et al.*, Nucl. Fusion **40**, 569 (2000).
[4] T. Obiki *et al.*, Nucl. Fusion **41**, 833 (2001).
[5] Y. Kondo *et al.*, Plasma Fusion Res. **15**, 2402064 (2020).
[6] E. Blanco and T. Estrada, Plasma Phys. Control. Fusion **55**, 125006 (2013).