Supplemental Material for "First experimental observation of Zonal Flows in the optimized stellarator Wendelstein 7-X"

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RADIAL CORRELATION ANALYSIS

In order to determine the radial scale of the ZF structure, a third DR system (DR-E1) was combined with the main one (DR-V1). DR-E1 is installed in the same port and antenna as DR-V1, meaning that both systems provide $u_\perp$ measurements at the same poloidal and toroidal location, only separated by a radial distance related to their frequency difference. When both frequencies coincide, DR-V1 and DR-E1 measure at the exact same point and therefore their signals show a very high correlation. By observing how such correlation decays as the radial distance between them is increased, the size of the fluctuating structure may be determined. In order to do so, a fine radial scan was carried out along with the normal frequency ramps in a number of experiments, including the reference scenario in discharge 230215051. In them, small frequency steps of 100 MHz were used in the synchronous frequency ramp of DR-V1 and V2. At the same time, DR-E1 measured at constant frequencies values at intermediate points of the scan (60, 62 and 64 GHz. See Figure 1 for a sketch of the frequency setup.

A characteristic result of this analysis is shown in Figure 2, where the sweep around 62 GHz (roughly corresponding to the $0.55 < \rho < 0.6$ region) is selected. In order to discriminate which part of the correlation between DR-V1 and DR-E1 can be related to the ZF structure, the local coherence is compared to that of the LRC between DR-V1 and DR-V2: As can be seen, two different frequency ranges can be defined: a low band ([0.4, 2.5] kHz) in which the LRC are relevant, and can therefore be associated to the ZF oscillations, and a high band for which no ZF activity is expected according to the LRC spectrogram ([8-20 kHz]). The behaviour of the radial coherence follows that of the LRC remarkably, with a clear radial widening of the coherent structure at the ZF-relevant frequencies. The radial correlation length of velocity fluctuations at the measurement location [1] can then be calculated taking these different regions into account. The results of such analysis are shown in Figure 3: first, the coherence spectrum between both signals is

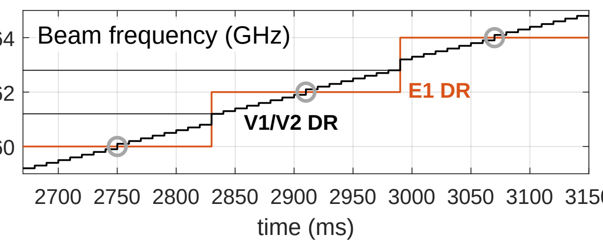

Figure 1. Frequency sweeps of all three DR systems for a typical 500 ms ramp. DR-V1 and DR-V2 (in black) carry out a fine radial sweep around the fixed frequency values of DR-E1 (in red)

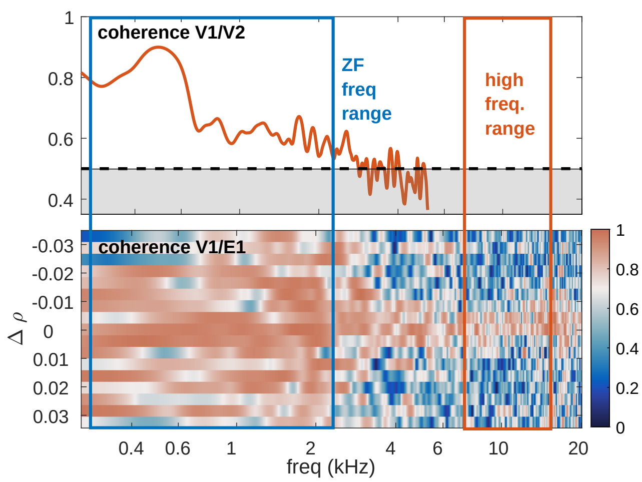

Figure 2. Frequency decomposition. Top: Experimental coherence between the toroidally separated DR systems. Bottom: Coherence between the two DR systems at the same location, as a function of the radial separation of their measurement points (displayed in the y-axis as a function of $\Delta\rho = \Delta r/a$). The two frequency ranges designated as "ZF frequency"/"high frequency" are indicated as overlayed blue/red boxes.

calculated for the combination of V1/E1 frequencies and characteristic values are averaged in the two frequency ranges. Then, the two averaged coherences are represented as a function of the DR-V1 measurement radial position. As could be expected, coherence is maximum

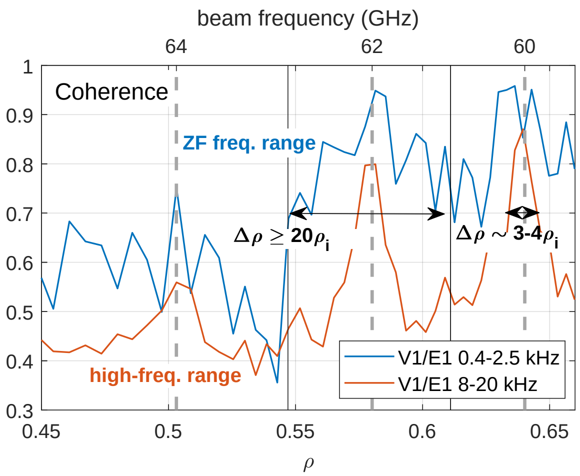

Figure 3. Radial correlation study. Coherence between DR-V1 and DR-E1 signals at different radii and frequency ranges. Vertical dashed lines indicate the fixed E1 frequencies/radii for which both DR are measuring at the same position. As a guide to the eye, the limits of the V1 scan around 62 GHz are highlighted in both figures as solid black lines.

for both curves at specific positions where the radial scan crosses the long frequency steps of DR-E1 (indicated in Figure 1 as three gray circles/dashed lines). However, the low frequency, ZF-relevant curve reaches higher coherence values and shows a much flatter radial decay, keeping substantial coherence values of $\gamma \simeq 0.7$ at the edges of the frequency scan (marked by thin black lines and spanning 1.6 GHz, corresponding to $\Delta\rho \simeq 0.05$). This can be interpreted as a lower bound for the radial correlation length which, taking minor radius $a = 0.5$ m and $T_i \simeq 1\,\text{keV}$, would yield a minimum radial width of the ZF of 2.5 cm or roughly 20 times the ion gyroradius (ρ_i). This is in good agreement with the ZF expected radial correlation length of several tens of ρ_i [2]. By contrast, the radial correlation length of the high frequency band corresponds to a few ρ_i, more in line with the typical values for common drift-wave turbulence.

TURBULENCE AND PARTICLE TRANSPORT MODULATION ANALYSIS

ZF are expected to modulate local drift turbulence [2] and have been found to modulate particle transport under certain scenarios [3, 4]. In order to evaluate this, the correlation of the $u_\perp$ and the density fluctuation signal from DR-V1 is calculated. The second is obtained by applying a 5 kHz high pass filter to the amplitude of the DR-V1 signal in order to avoid a possible instrumental correlation to $u_\perp$ and to select the high frequency turbulence expected to be modulated by the ZF. The RMS of this filtered component provides an envelope of the high frequency fluctuations, which is then cross-correlated with

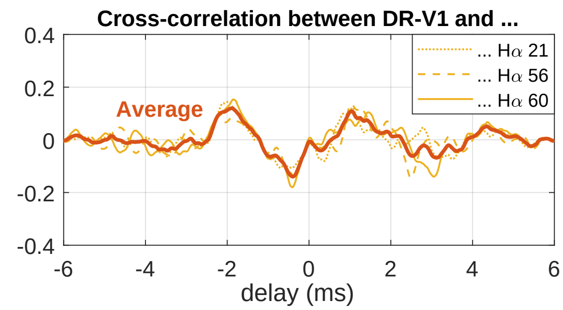

Figure 4. Cross-correlation of core DR-V1 $u_\perp$ with three Hα channels from the filterscope. Red line indicates average correlation of all three channels.

the $u_\perp$ measured by the same DR at the outer core region where the LRC were detected. As well, the potential effect of the ZF in global transport is investigated: For this, the flow oscillation measured by DR-V1 is cross-correlated with three channels from the W7-X filterscope system [5] measuring Hα (21, 56 and 60), which can be taken as a proxy for particle fluxes escaping the confined plasma [3]. In this case, a conditional analysis has been carried out, selecting only frequency windows on the DR for which the LRC was strongest, with a cross-correlation at zero delay of at least 0.45. This resulted in seven radial positions between $\rho = 0.55$ and $\rho = 0.64$, over which the correlation is averaged for each of the Hα signals. The results, shown in Figure 4, are very similar for these three independent measurements and display a 300 – 400 Hz oscillation with a maximum anticorrelation value of −0.2 at a delay of around −350 ms (indicating that the $u_\perp$ oscillation precedes the reduction in Hα emission). The frequency and delay values are close respectively to the ZF frequency found in both experiments and GK simulations (around 500 Hz) and to the particle confinement time of W7-X, $\tau_p \simeq 260$ ms [6], which might be an indication that the ZF would be causing some level of modulation on the particle outflux. However, the correlation level is rather low, and the agreement in frequency and delay only qualitative, so no clear conclusion can be obtained here. In any case, in view of these inconclusive observations, it seems justified to state that even if this modulation is caused by the ZF, it does not lead to a major contribution to global transport.

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