# First Experimental observation of Zonal Flows in the optimized stellarator Wendelstein 7-X

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Optimized stellarators are a promising approach for a fusion reactor, in which a careful design of the magnetic geometry substantially reduces neoclassical transport. In recent years, this concept has been successfully tested in its flagship device Wendelstein 7-X (W7-X) [1]. While improved performance with respect to non-optimized stellarators has already been demonstrated in W7-X [2], this was only the case in specific scenarios for which turbulence could be effectively suppressed [3]. More generally, turbulent transport has proven a major limitation for the achievement of high performance in W7-X [4] and its reduction is now one of the main objectives of further advancements of stellarator optimization. In this sense, experimental characterization of turbulence in W7-X is of paramount importance to develop improved operational scenarios. In particular, one of the central features of plasma turbulence are zonal flows (ZF), quasi-stable, slowly oscillating structures of the electrostatic potential that are constant on flux surface ($k_\phi = k_\theta = 0$) and possess a radial structure ($k_r > 0$) [5]. While ZFs do not directly cause cross-field transport, they are expected to indirectly regulate it by acting as an energy sink and giving rise to sheared flows capable of decorrelating turbulent structures [6]. Thus, a proper experimental characterization of ZF and its validation against turbulence simulations is of great importance to enable the reactor-relevant predictive transport calculations of first-principles gyrokinetic (GK) codes in optimized stellarators. Detection of zonal flows is particularly challenging both experimentally, as it is typically carried out by detecting long range correlations (LRC) between potential or $E_r$ fluctuations, and numerically, as it involves CPU time-intensive low oscillation frequencies. In order to determine their zonal character, measurements must be carried out at remote positions not directly connected through a field line, which generally requires dedicated experimental layouts with duplicated diagnostics such as HIBPs or probes [7,8]. Such layout was devised in W7-X, with two twin Doppler reflectometers (DR) installed at two toroidally separated ports. This system has become available for the first time in the last experimental campaign (November 2022-April 2023), allowing for the direct measurement of LRC between distant measurements of flow oscillations [9]. In this work, we conduct an extensive analysis of these LRC for a range of W7-X ECRH-heated plasma scenarios featuring different densities and heating powers. As a result, radial regions are discovered in which significant cross-correlation is measured: First, a low frequency (ca. 1 kHz) coherent mode is detected in the plasma edge, which is determined not to be a ZF: A finite cross-phase is present between the two DR measurements and other diagnostics showed that the mode had finite poloidal/toroidal wavenumbers and its fluctuations were also observed in density and plasma current, in good agreement with previous reporting of this mode [10]. However, a significant LRC is detected deeper in the core for which all experimental signs indicate zonal activity: Both flow measurements oscillate in phase, indicating ($k_\phi \sim k_\theta \sim 0$), are less coherent (siting in the 0.5-3 kHz frequency band), feature a radial width of at least 2.5 cm ~ $20\rho_i$ and comparison to other diagnostics reveals an electrostatic nature and absence of LRC in density fluctuations. Finally, the evolution of the zonal-component of turbulence was calculated by means of non-linear simulations with GK codes, including independent simulations in flux-tube geometry with kinetic electrons (stella) and in global geometry with adiabatic electrons (EUTERPE). Remarkable agreement with these simulations indicate that experimental results are consistent with theoretical predictions of ZF activity in W7-X.

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