Zonal Flows in stellarators: Experimental measurements, code validation and implications for future reactors

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The recent detection of zonal flows (ZF) in the optimized stellarator Wendelstein 7-X (W7-X) [1] will permit for the first time their experimental characterization in reactor-relevant conditions [2]. Besides, the remarkable agreement achieved with predictions from extensive GK simulations can be seen as a general validation of our understanding of ZFs in non-axisymmetric geometries. This milestone marks a new level of maturity in ZF studies in stellarators, now on par with tokamaks, and calls for a critical assessment of the corpus of work from recent years in order to compile what has been learnt and, more importantly, plan whichever next steps are required in this field in order to validate transport predictions for future stellarator reactors.

With this aim, we will review the main experimental results from two key devices: the large, reactor-relevant W7-X, and the medium-sized TJ-II, in which two decades of research in ZF have yielded some of the most advanced results yet in this field, including the development of experimental techniques later applied in W7-X. This discussion will be linked whenever possible to the comparison to numerical simulations and the validation of theoretical models. First, general experimental characterization of ZFs has been the subject of intense study, ranging from the early probe observations in TJ-II [3] to the full radial scan carried out recently by means of the unique dual Heavy Ion Beam Probe system [4] or the aforementioned detection in W7-X using Doppler reflectometry (see figure 1, left) [1]. From all these experimental works, a number of consistent ZF features emerge, such as the electrostatic nature and low frequency of their oscillations, or the large radial size in the order of tens of ion gyroradii. As well, computationally expensive nonlinear GK simulations have been carried out in order to reach the long time scales involved, showing remarkable agreement with the experimental observations (see figure 2, left). Then, the role of ZF in transport has been specifically addressed by a number of additional works: correlation between H_α monitors and surface-uniform E_r oscillations provides an empirical method to discuss the modulation of global transport by the ZF [5] (see figure 1, right) which has

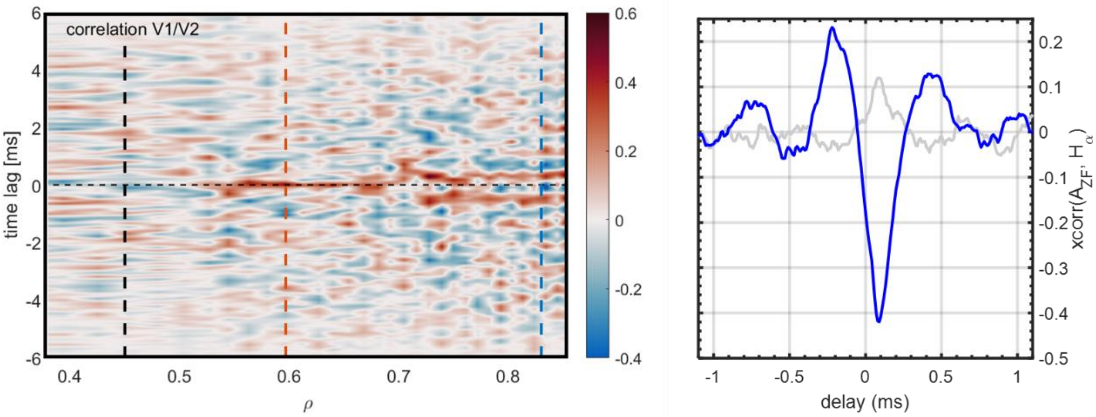

Figure 1: On the left, radial profile of the correlation between two remote Doppler reflectometer systems in W7-X, showing the ZF signature at the outer core (ρ ~ 0.6) [1]. On the right, correlation between a TJ-II H_α monitor –proxy for the particle outflux- and the global E_r oscillations, showing the modulation of particle transport by the ZF [5].

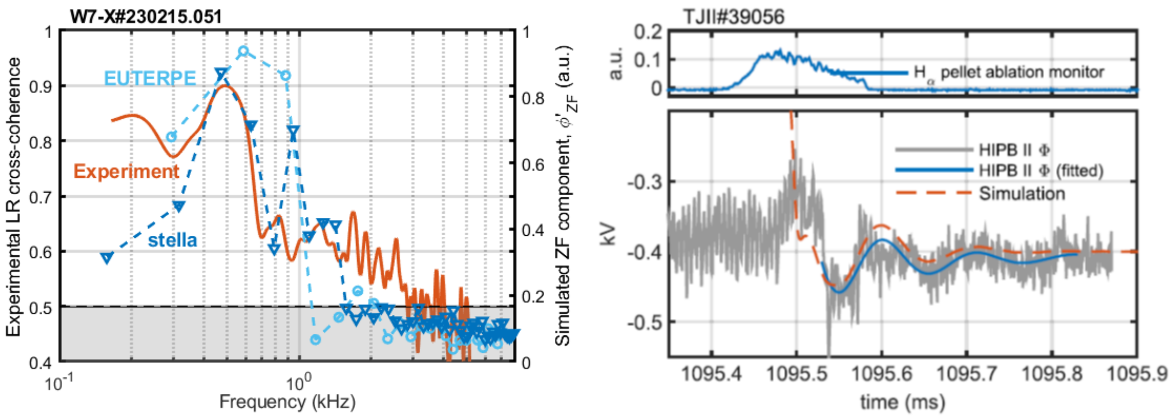

Figure 2: On the left, comparison between experimental long range cross-coherence in W7-X and the spectrum of the ZF component obtained by non-linear GK simulations [1]. On the right, experimental measurement of the damped oscillation of electrostatic potential following a pellet injection in TJ-II, along with the evolution obtained in a Rosenbluth-Hinton GK simulation [7].

been applied both in TJ-II and W7-X. These effects will then be compared to transport predictions from GK simulations in order to check their predictive capabilities. Moreover, a detailed analysis of turbulence during the access to improved confinement regimes in TJ-II confirmed the role of large sheared flows in the formation of transport barriers, consistent with models in which the L-H transition is triggered by ZF [6]. Finally, a last set of studies have been dedicated to verify the theoretical description of ZF in non-axysimmetric geometries: Unlike tokamaks, stellarators display a characteristic oscillatory relaxation of zonal electrostatic potential perturbations even in non-collisional plasmas. This was successfully measured in TJ-II, where the zonal perturbation was created by means of a pellet injection [7], and the characteristics of the oscillation were reproduced by linear GK simulations, in which the importance of considering realistic impurity concentrations was shown [8] (see figure 2, right). The importance of this result is not limited to the validation of the fundamental mechanism regulating ZF in stellarator: damping properties could be representative of non-linear saturation levels and heat transport coefficients, but can be calculated by simple linear simulations [9], thus making them a valuable proxy for turbulent transport in stellarator reactor optimization efforts.

Once an overview of our current knowledge of ZFs in stellarators has been provided, the main implications for a stellarator fusion reactor will be discussed: Results from the last campaigns in W7-X have shown that, despite neoclassical optimization, confinement values required in a reactor will not be accessible unless turbulent transport can be sufficiently suppressed. In this sense, ZF are expected to play a determinant role both in the achievement of high performance regimes [10] and in determining the general level of turbulent transport [11]. More critically, reactor scenarios involve plasma conditions not generally achieved in today's machines, but which will lead to new ZF physics, such as their amplification by fast particle populations [12], or their potential role in the degradation of confinement as high β is approached and ZF erosion leads to mixed subdominant KBM-ITG turbulence [13]. These new physics will be reviewed through the prism of reactor physics, thus focusing on the next steps required both in experimental and simulation efforts in order to fill the gaps in our current understanding.

[1] Carralero et al. PRR (2025) [2] Wolf et al. NF (2017)., [3] Pedrosa PRL (2008) [4] Hidalgo et al., NF (2022) [5] Alonso et al., NF (2012) [6] Estrada et al., PRL (2011) [7] Alonso PRL (2017) [8] Sanchez, PPCF, 2018 [9] Nunami, PoP (2013) [10] Zocco et al., PRR (2024) [11] Warmer PRL (2021) [12] Di Siena et al., PRL (2021) [13] Mullholand et al., PRL (2023)