

First experimental observation of zonal flows in the optimized stellarator Wendelstein 7-X

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In this work, we present the first experimental evidence of the presence of zonal flow (ZF) structures in the optimized stellarator Wendelstein 7-X. Using an assortment of diagnostics, flux surface-uniform, electrostatic flow oscillations have been measured, showing a radial scale in the range of tens of ion gyroradii. As well, indications are found of local turbulence being modulated by the ZF. Measurements show remarkable agreement with the ZF predicted by nonlinear gyrokinetic simulations. These results represent the first direct measurement of ZF in a large stellarator suitable for the validation of models in reactor-relevant conditions.

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Introduction. Zonal flows (ZF) are a universal characteristic of stratified turbulent systems which can be found in many different natural media such as oceans, planetary atmospheres, or the solar convection zone [1], where they manifest as system-sized flows perpendicular to the stratification. ZF can as well be found in some laboratory settings such as magnetic fusion experiments, in which high-pressure plasmas are confined by means of strong magnetic fields arranged in nested flux surfaces. Plasma parameters are roughly constant along these surfaces, so ZF take the form of surface-uniform oscillations of the $\mathbf{E} \times \mathbf{B}$ flow u_E , perpendicular both to the magnetic field $\mathbf{B}$ and the electric field $\mathbf{E}$, normal to the surface and thus aligned with the stratification direction [2]. In this context, ZF are excited through nonlinear coupling of unstable microscale modes (typically drift-wave turbulence, possibly amplified by other mechanisms such as interaction with fast particles [3]) and are supposed to play an important role in confinement. While not directly causing advection perpendicular to flux surfaces, they might regulate cross-field turbulent transport by a number of mechanisms including suppression of turbulence by shear flows [4], stabilization of drift modes by inverse cascade energy transfer [2], or govern saturation by the activation of large-scale damped modes [5]. This central role in turbulence regulation makes a proper characterization of ZF in reactor-relevant plasmas of paramount importance for the development of a fusion reactor, and particularly so for a stellarator reactor: Initial operation of Wendelstein 7-X

(W7-X) [6] has demonstrated that optimization can reduce collisional transport associated with the stellarator-characteristic three dimensionality of the magnetic field (usually termed “neoclassical transport”) to acceptable levels, while retaining all their advantages over tokamaks, such as the absence of disruptions, easier access to steady-state operation, etc. [7]. However, the first experimental campaigns have shown that turbulence typically dominates transport and confinement levels consistent with reactor requirements can only be achieved in selected scenarios in which turbulence is suppressed [8,9]. In this context, ZF are expected to be determinant in the reduction of turbulent transport: gyrokinetic simulations indicate that scenarios with suppressed turbulence in W7-X could be caused by a surge in ZF amplitude [10]. More generally, a stronger ZF is also associated to the improved confinement in the inward-shifted configuration in the similarly sized LHD heliotron [11], as well as to the lower turbulent transport in the later when compared to W7-X [12]. So far, attempts to confirm these results have been hampered by the fact that no ZF had ever been detected in a large stellarator. In this work, we present the first experimental detection and characterization of ZFs in W7-X, thereby setting the foundation for a new line of research on this key mechanism. Since this device is expected to achieve fusion-relevant plasma parameters when fully powered [6], such new line might eventually be critical for the validation of our current models for the regulation of transport in a future stellarator reactor.

Experiments. Empirical observation of ZF is a daunting endeavor: Given the flux surface uniformity of ZF, their most distinctive experimental signature is the presence of long-range correlations (LRC), significant cross-correlation levels between measurements of velocity oscillations carried out in distant, magnetically disconnected positions of the same flux surface. This is a demanding technique, as it typically requires duplicated fluctuation diagnostics such as Langmuir

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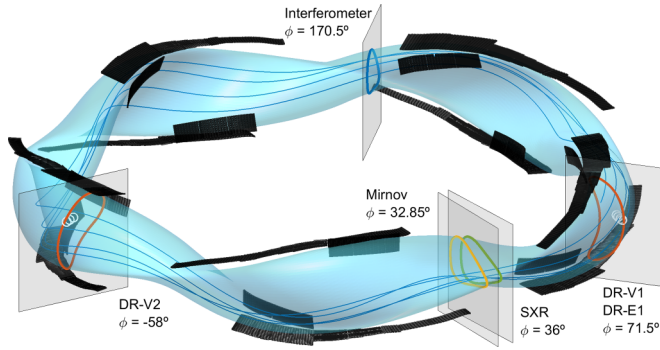


FIG. 1. Experimental layout at W7-X. Last closed flux surface and divertors are indicated as blue shade and black structures. The toroidal plane and its intersection with the separatrix at each diagnostic position are indicated as gray squares and colored curves. DR measurement areas are highlighted by white circles. Blue line shows two toroidal turns in each direction of a flux tube crossing the $\rho = 0.7$ measuring position of DR-V1.

probes or heavy-ion beam probes (HIBP), which have been used for the detection of ZF in most studies in the literature [13–15]. In W7-X, a dual Doppler reflectometer (DR) system has been developed and recently commissioned with the main objective of carrying out this kind of measurements. As can be seen in Fig. 1, each DR (named DR-V1 and DR-V2) is installed in one of two sections located 129° toroidally apart, and their measurement regions are not directly connected by a field line. These diagnostics measure the Doppler-displaced back-scattered component of a V-band microwave beam propagating in the O mode, from which the local perpendicular velocity $u_\perp \simeq u_E$ and amplitude of density fluctuations can be calculated. More details on the DR system and the approximations involved can be found in Refs. [16–19]. Both DR carry out synchronized radial sweeps with frequency being changed in discrete 1 GHz steps of 10 ms duration to probe a range of radial positions. Ray-tracing analysis carried out with TRAVIS [20] showed that, for the regions discussed in this work, this synchronization led to a radial separation between the two measurements in the 1–2 mm range. The 10 MHz sampled complex-amplitude signals are binned and Fourier transformed in order to obtain a measure of the Doppler peak-frequency oscillation, from which a temporal trace of $u_\perp$ can be calculated for each DR with a time resolution of tens of μs [21]. Finally, the cross correlation of the two $u_\perp$ signals is calculated in order to obtain the LRC. In this work, we analyze discharges of intermediate density ($\bar{n}_e \simeq 6.5 \times 10^{19} \text{ m}^{-2}$) carried out in the standard magnetic configuration, on which 5 MW of electron-cyclotron resonance heating is applied. In them, the only relevant island chain is formed by the 5/5 rational just outside the separatrix in order to form the island divertor. These parameters correspond to a baseline scenario, in which transport is dominated by strong ion-scale turbulence leading to poor performance [9,22,23]. A representative result of the dual DR LRC is shown in Fig. 2, which shows $u_\perp$ signals from both DR at three different radial positions, as well as a correlogram of the two signals for the whole full V band, covering a range of measurements for $\rho = [0.4 - 0.85]$ ($\rho = r/a$, the effective minor radius coordinate normalized by the minor radius of the plasma). At $\rho \simeq 0.85$ (“edge”) a strongly

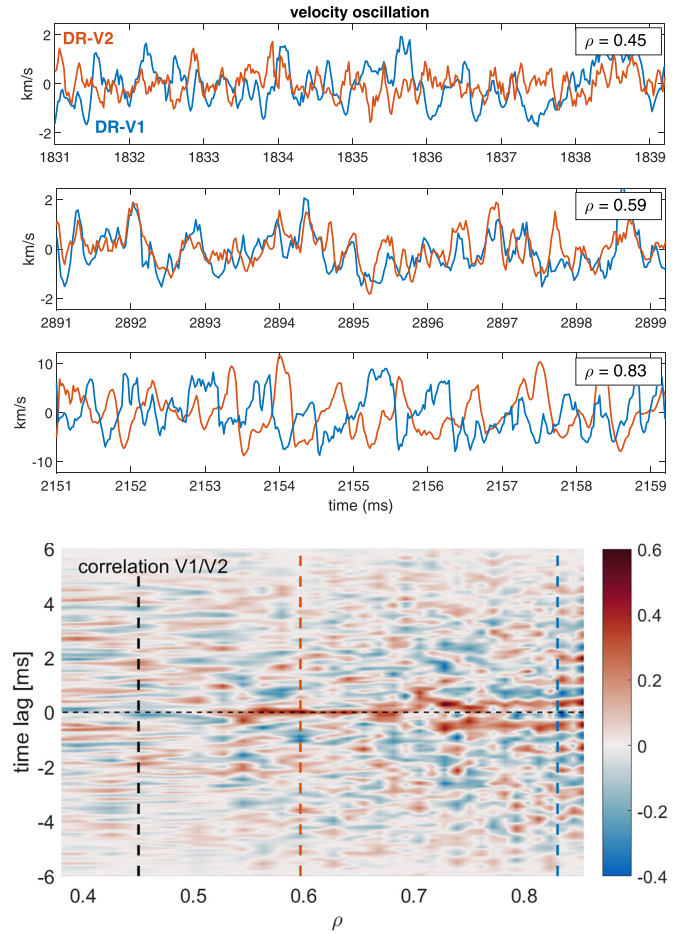


FIG. 2. Dual-reflectometer signal analysis from reference discharge 20230215.051. Top: $u_\perp$ signals from DR-V1 and DR-V2 at three radial positions. Direct current component has been filtered out in them. Bottom: cross correlation of the two signals. Each position at the x axis corresponds to a common DR beam frequency, resulting in a different radial location for the measurement (as indicated by the white circles in Fig. 1.) Positions from the top plot are indicated by a dashed line.

coherent mode is marked by the presence of regular positive and negative lobes. This mode has a well-defined frequency of 1.2 kHz, and displays a clear antiphase between DR-V1 and DR-V2. As a result, signals display strong and relatively regular oscillations with peaks of up to 10 km/s, and roughly opposing phases in each channel. These signatures are not the ones expected for a ZF, but instead match a well documented edge magnetohydrodynamic (MHD) mode for which a range of diagnostics report the same 1.2 kHz frequency in a very similar plasma scenario (see, e.g., Ref. [24]). Around $\rho \simeq 0.6$ (“outer core”), the lack of lobes and maximum value at time lag $\tau = 0$ reveal a strong, zero-phase correlation caused by some noncoherent oscillation, which ranges between a few hundred Hz and 2 kHz. This can be appreciated in the signals even by the naked eye, as was the case with the HIBP measurements reported in Ref. [13] (although it should be noted that no band filter has been used here to improve the match). Interestingly, a similar modulation can be seen in estimated flows from line-integrated PCI measurements [25]. Finally, at $\rho \simeq 0.45$ (“inner core”) both signals are clearly different,

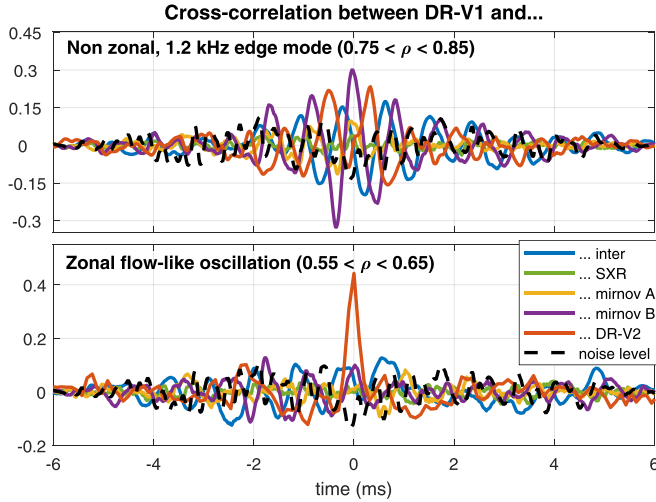


FIG. 3. Top/bottom plots show the cross correlation of DR-V1 measurements at the edge/outer core regions with other diagnostics. Noise level is represented as a dashed line.

and no LRC is detected. This is caused by a strong decay in the quality of the DR-V2 signal for $\rho < 0.5$, so the presence of ZF can't be excluded in this region. Similar results have been obtained in other frequency ramps carried out in other discharges, as well as at different times during an interval exceeding 2 s in which plasma conditions were constant. This indicates the nontransient nature of the described structures.

The detection of an MHD mode in the edge along with the ZF in the core allows for a comparative study aimed to confirm the absence of density and current fluctuations associated to the velocity oscillations in the latter [2,14]. In order to do this, the $u_{\perp}$ measurements by the DR are cross correlated with traces from several diagnostics: First, a fast-line-integrated density signal from the interferometer [26]; second, soft x-ray (SXR) measurements from a range of chords corresponding to the radial region covered by DR [27]; finally, magnetic-field fluctuations measured by a number of Mirnov coils [28]. These diagnostics are placed in different toroidal and poloidal locations, as indicated in Fig. 1. The results can be seen in Fig. 3, where cross correlations are presented along with the average LRC between DR-V1 and DR-V2 for the same radii. For clarity, only one SXR chord (2A-20, crossing the whole plasma section) and two Mirnov signals (11-120 and 11-440, separated poloidally roughly 90°) have been selected as the most representative. Finally, the cross correlation between the two DR in the inner core (where DR-V2 is pure noise) is represented in both plots as a reference of the background noise level of the analysis. As can be seen in the figure, results are very different at the edge and core regions: at the edge, significant correlation appears for all diagnostics, with substantial phase differences between them. This is consistent with current and density fluctuations and finite-mode numbers associated to the MHD mode reported in literature (in particular, $m = -3$, $n = 2$, according to Ref. [24]). In contrast, results in the core are clearly consistent with a ZF signature. As can be seen in the lower plot of Fig. 3, the only cross correlation above the noise level is the LRC between DR-V1 and V2, indicating that the noncoherent velocity oscillation

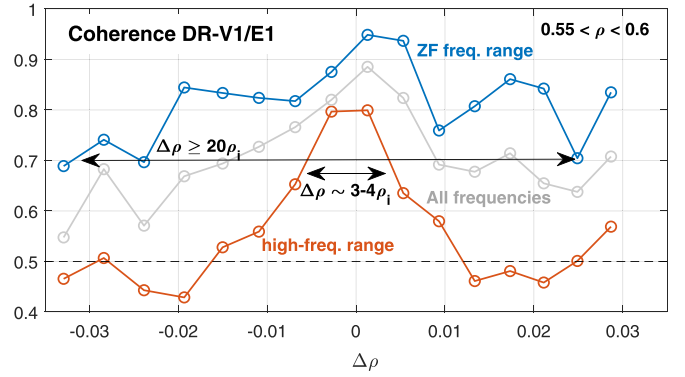


FIG. 4. Coherence of DR flow measurements as a function of radial distance $\Delta\rho = \Delta r/a$. Blue/red colors indicate the use of filters to isolate the ZF frequency/high-frequency range. Coherence of the full spectrum is shown in grey.

is not only in phase at the two remote DR systems, but also not associated to the current or density fluctuations detected by the other diagnostics, as expected for the flux-surface-uniform, electrostatic oscillations of a ZF. As well, the lack of correlation with SXR signals excludes effects associated to oscillations in the density or pressure profiles. An additional ZF characteristic of the core oscillation can be found by a radial-correlation analysis carried out with a third DR system launching on the same antenna as DR-V1 [29]. As can be seen in Fig. 4, the radial scale of the oscillation at ZF relevant frequencies (the 0.4–2.5 kHz for which high LRC are observed) is at least 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]. In contrast, the radial correlation length of the high-frequency band (8–20 kHz) corresponds to a few ρ_i , more in line with the typical values for common drift-wave turbulence.

Finally, the relation between flow oscillations and the density fluctuations measured by the DR-V1 is investigated [29]: As can be seen in Fig. 5, a clear anticorrelation appears between the two. As in Fig. 2, the modulation is clear enough to be seen in their time traces, which feature visibly opposing maxima and minima. This result is consistent with other studies [30] and indicates clearly that the ZF has a modulating effect on local turbulence. Flow oscillations are also cross correlated to $H\alpha$ measurements to investigate potential effects in the global transport [31]. While some signature of modulation can be seen in this analysis, the results are nonconclusive and indicate that in any case, such effect would be small [29]. The ZF seems to have a clear impact on local turbulence—most likely acting as an energy sink and reducing it to some extent—but this does not seem to be sufficient to cause a substantial effect on global transport in this kind of discharges. This is not only consistent with the small amplitude of the ZF modulation relative to average values of the bulk velocity (σ/μ of $u_{\perp}$ is around 7% for ZF-relevant intervals), but also with the analyzed scenario, in which strong turbulence is known to dominate transport. An enhanced ZF leading to a clear stabilization of turbulence should be observable instead in high-performance scenarios [10], which will be investigated in forthcoming W7-X campaigns.

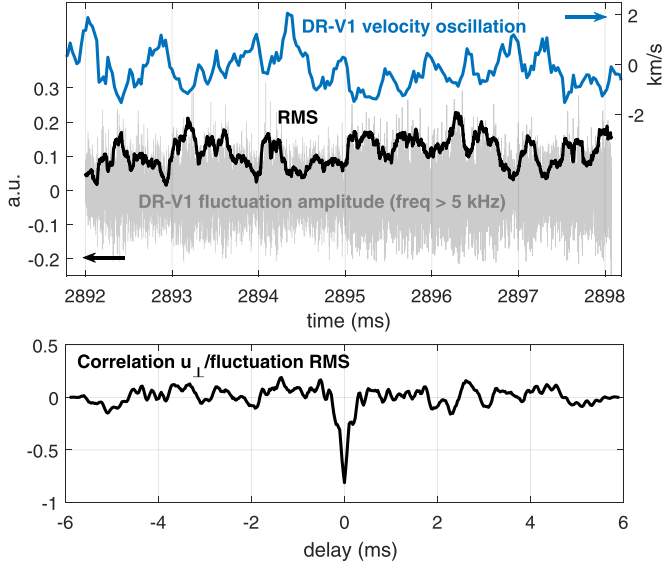


FIG. 5. Top: Time traces of flow oscillations/frequency fluctuations over 5 kHz/RMS are presented in blue/gray/black during the ZF-relevant window of Fig. 2. Bottom: Cross correlation of core DR-V1 $u_{\perp}$ and RMS of density fluctuations.

Simulations. In order to substantiate this experimental identification, measurements are compared to nonlinear gyrokinetic (GK) simulations carried out with realistic plasma profiles. First, radially global simulations with adiabatic electrons were carried out with EUTERPE [32] covering the $0.2 < \rho < 0.9$ domain. A period (one fifth) of the full stellarator is simulated with a spatial resolution similar to that used in Ref. [33], which allowed for a good convergence. Source term and weight smoothing are used as in Ref. [34] to keep the density and temperature profiles stable and reduce numerical noise in the (very long) nonlinear saturated state. The evolution of the zonal potential (defined as the flux surface-uniform component of the electrostatic potential ϕ_{ZF}) is monitored in the region $0.5 < \rho < 0.7$, keeping aside two buffer regions to limit the effect of the inner and outer boundaries. From this, the radial derivative giving rise to the zonal flows ϕ'_{ZF} is calculated. Second, simulations with kinetic electrons were performed with the code stella [35] in flux-tube geometry. In order to best approximate experimental observations, the radial position $\rho = 0.6$ and the flux tube centered with respect to the bean-shaped poloidal cross section of the plasma were considered, extending the flux tube two turns toroidally (following a field line equivalent to the one depicted in Fig. 1). As before, the code calculates the ϕ'_{ZF} from which u_E can be obtained (both ϕ'_{ZF} definitions are equivalent, although stella-specific details can be found in Ref. [36]). It must be noted that all these simulations are extremely intensive in computation resources, as exceptionally long times are required to resolve the sub-kHz ZF oscillations. Stella and EUTERPE consumed in the order of 2×10^5 and 10^6 CPU-hours respectively for simulating around 5 ms (equivalent to roughly $5000 \times a/v_{th,i}$, with $v_{th,i}$ the thermal speed of the ions). As an example, the evolution of ϕ'_{ZF} at $\rho = 0.55$ obtained by EUTERPE for reference discharge 20230215.051 is displayed on the top plot of Fig. 6. The bottom plot shows the spectrogram of ϕ'_{ZF} over

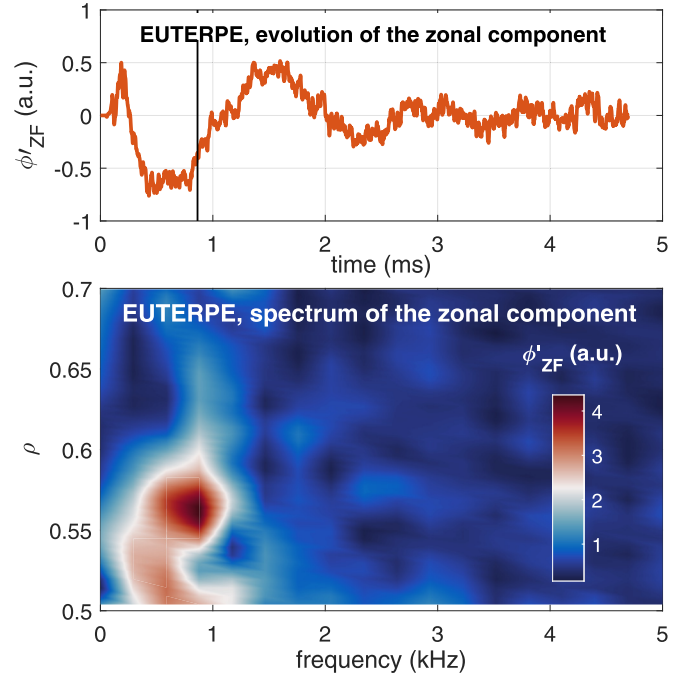


FIG. 6. EUTERPE GK simulations. Top: Evolution of the zonal component of a typical run. Bottom: Power spectrum vs radius and frequency for the zonal component.

the $0.5 < \rho < 0.7$ radial range. As can be seen, the simulation correctly captures the radial localization of the ZF in the experiment (the $\rho < 0.6$ localization surrounded by an outer, activity-free region matches qualitatively with the zero-phase LRC at Fig. 2) and indicates a peak frequency for the ZF in the sub-kHz range, which can be identified in the top plot of Fig. 6 as well as in equivalent evolution plots obtained by stella. Finally, a direct comparison between both simulations and experiments is presented in Fig. 7: In it, the spectrum of the long-range coherence between DR-V1 and V2 is calculated reducing the Nyquist frequency to some 5 kHz in order to

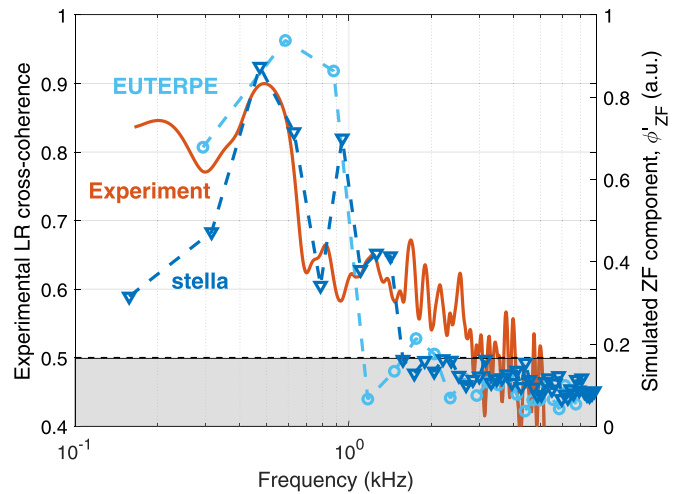


FIG. 7. Comparison between GK simulations and experimental results. Grey shaded area indicates nonmeaningful experimental cross coherence.

obtain several subsamples to average, thus ensuring that the minimum statistically meaningful coherence is $\gamma_{V_1, V_2} = 0.5$ [37] (the nonmeaningful region below that value is indicated as a shaded area in the figure). As can be seen, the coherence peaks at around 500 Hz and remains significant up to around 3 kHz. This result is compared to the ZF component spectra from both simulations, taking $\rho = 0.55$ position in the case of EUTERPE as representative of the ZF activity displayed in Fig. 6. The three curves show a remarkable agreement in the structure and frequency of the peak, which appears, respectively, for 470 and 580 Hz for stella and EUTERPE. As well, qualitative agreement is reached on the spectral range for which the LRC are detected at the experiment (up to 3 kHz) and simulations (up to ca. 2 kHz).

Conclusions. In conclusion, positive evidence for the existence of ZF in Wendelstein 7-X is presented for the first time: First, LRC analysis between two remote DR proves the existence of a global structure in $u_\perp$ oscillations measured in the $0.55 < \rho < 0.65$ region (deeper radii can not be probed due the loss of DR signal) and in a spectral range between a few hundred Hz and around 3 kHz. This result is so clear that can be seen directly in the unfiltered raw data shown in Fig. 2. Second, comparison to other diagnostics reveals the electrostatic nature of the structure. This result clearly departs from the correlation to current and density fluctuations measured at the edge mode in $\rho \geq 0.75$, in good agreement with previous reports. Third, an additional analysis of the mode structure carried out with a third DR yields a radial size of at least 20 ion gyroradii, much higher than that of conventional drift-wave turbulence and consistent with theoretical expectations. This

ZF is shown to modulate local turbulence amplitude, but no major effect of such modulation on global transport is found, as is to be expected in the analyzed turbulence-dominated scenario. Finally, the frequency spectra of the LRC shows a remarkable agreement with the predicted ZF component of independent nonlinear gyrokinetic simulations, which were extraordinarily CPU intensive in order to resolve the low frequencies involved. The groundbreaking importance of this result comes not just from the fact that theoretical predictions regarding a key feature of the turbulent system regulating transport in an optimized stellarator have been experimentally confirmed, but also from the first time detection of ZF in a machine capable of reactor-relevant plasmas, which opens a new line of turbulence experimental research and theory validation with direct implications for next-generation devices.

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