Electrostatic turbulence and transport in a simple magnetized plasma\textsuperscript{a)}

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Gradient driven electrostatic instabilities are investigated in TORPEX [A. Fasoli, B. Labit, M. McGrath, S. H. Müller, M. Podestà, and F. M. Poli, Bull. Am. Phys. Soc. 48, 119 (2003)], a toroidal device \((R=1 \text{ m}, a=0.2 \text{ m})\) in which plasmas are produced by microwaves \((P \approx 20 \text{ kW})\) with \(f_{\text{rf}} = 2.45 \text{ GHz}\), in the electron cyclotron frequency range. Typical density and temperature are \(n_e \approx 10^{17} \text{ m}^{-3}\) and \(T_e \approx 5 \text{ eV}\), respectively. The magnetic field is mainly toroidal \((\approx 0.1 \text{ T})\), with a small vertical component \((\approx 0.4 \text{ mT})\). Instabilities that can be generally identified as drift-interchange waves are observed and characterized for different levels of collisionality with neutrals. The frequency spectrum and the spatial profile of the fluctuation-induced flux are measured. An 86-tip probe is used to reconstruct the spatio-temporal evolution of density structures across the plasma cross section. The measured structures are characterized statistically, and related quantitative observables are constructed. © 2006 American Institute of Physics. [DOI: 10.1063/1.2178773]

I. INTRODUCTION

Most magnetic confinement schemes are affected by levels of particle and energy transport across the magnetic field that are much higher than those induced by collisional processes.\textsuperscript{1} Although it is now universally accepted that such transport is caused by turbulent fluctuations in the plasma, the path from linear instabilities to turbulence and the quantitative link between turbulence and transport are far from being fully understood.\textsuperscript{2} Tokamak research in the past decade progressed significantly towards an empirical reduction of transport. In several advanced regimes, transport has been reduced to levels close to the neoclassical predictions, at least for the ion channel.\textsuperscript{3–6} In parallel with these developments, a large effort has been undertaken in theory and numerical simulations to interpret these observations and provide a physics basis for developing methods to reduce anomalous transport.\textsuperscript{7}

Unfortunately, intrinsic difficulties prevent systematic comparisons of theoretical results with experimental data in fusion devices. Gyrokinetic simulations are able to reproduce some of the observed features in the plasma core microturbulence,\textsuperscript{8,9} and yield the spatio-temporal evolution of turbulent structures, but cannot generate long time series for several reasons, including numerical stability and computing time. Fusion experiments suffer from an opposite limitation. Although time series and related probability distributions are relatively easy to measure locally, particularly at the plasma edge,\textsuperscript{10,11} the difficulty in diagnosing fluctuations in hot plasmas restricts the reconstruction of the turbulence evolution to limited portions of the plasma cross section and of the frequency and wave number spectra.\textsuperscript{12,13}

These difficulties motivate the development of basic plasma physics experiments dedicated to fluctuations, turbulence and transport studies, which offer better diagnostic access and more flexibility in the use of control parameters.\textsuperscript{14–17} Provided suitable observables for comparisons are defined, observations from these relatively cold and low density plasmas can be used as reference cases for fluid simulations, which, in addition to producing spatio-temporal information, can be run long enough that time series statistics are meaningful.\textsuperscript{18,19}

Some aspects of the physics of waves related to turbulence and cross-field transport can be addressed in linear devices,\textsuperscript{20,21} but toroidal geometry is important in order to have the ingredients that drive turbulence in fusion experiments; namely, magnetic field line curvature in combination with plasma gradients. The experiments reported herein are performed on TORPEX,\textsuperscript{22} a simple toroidal plasma, confined by a primarily toroidal magnetic field, with no induced current or rotational transform. In such configuration no trapped particle or magnetic shear effects are present, and, due to the low plasma pressures, electromagnetic and \(\beta\) effects need not be taken into account (typically, \(\beta=2\mu_0nT/B^2 \ll 10^{-3}\)).

The goal of this paper is to fully characterize the electrostatic instabilities naturally occurring in TORPEX plasmas, from their local characteristics (dispersive properties, fluctuation-induced transport, and statistical features), to a reconstruction and a quantification of the macroscopic spatio-temporal features. The experimental conditions are varied using one of the several available control parameters, the neutral gas pressure. Although the plasma parameters and the open magnetic configuration carry similarities with tokamak edge plasmas, the general relevance of these studies should not be sought in the properties of the particular instabilities that appear, which are likely to be of different nature, or in different regimes from those affecting fusion devices, but in the physics behind the complete sequence of mechanisms.

After a description of the experimental setup, including the confinement scheme, the plasma production process and

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the main diagnostics (Sec. II), the structure of the paper reflects the four main steps undertaken in this investigation. Section III deals with the identification of the instabilities and their driving mechanisms. Measurements of the fluctuation-induced particle flux are introduced in Sec. IV, while Sec. V discusses the statistical properties of the fluctuations. Spatio-temporal imaging of the electrostatic fluctuations is described in Sec. VI, which includes a quantitative characterization of the observed structures along with a definition of observables upon which comparisons with theory can be based. Finally, a discussion of the findings of the paper and indications on possible future developments are contained in Sec. VII.

II. EXPERIMENTAL SETUP

TORPEX is a recently constructed toroidal device with major and minor radius $R=1$ m and $a=0.2$ m, and a toroidal magnetic field up to 0.1 T. With a purely toroidal magnetic field, charge-dependent grad $B$ drifts give rise to a vertical electric field, which leads to very fast particle losses due to $E \times B$ drifts. To partly short-circuit the electric field and reduce these losses, a small vertical component ($\approx 4$ mT) is added.

In the presence of a vertical magnetic field, at equilibrium, a vertical electric field ($E_{\text{eq}}$) forms in the plasma and draws parallel currents that compensate the grad $B$ flux. The zero-order particle transport is thus determined by two loss mechanisms: the $E_{\text{eq}} \times B$ flow and the direct loss where the field lines intersect the vacuum vessel. By increasing the field line pitch angle, the end-of-field line loss increases, but $E_{\text{eq}}$ decreases; thus, the first loss mechanism loses importance. An optimum pitch angle exists, at which the particle confinement time is maximum. The dependence of the confinement time on the pitch angle, the value of the vertical field maximizing the confinement, and the maximum value of the confinement time were calculated theoretically and verified experimentally, on TORPEX and elsewhere.

Highly reproducible plasmas of H, He, and Ar, with density, electron temperature, and plasma potential in the range $n_e \approx 10^{16}$–$10^{17}$ m$^{-3}$, $T_e \approx 5$–10 eV, and $V_p \approx 10$–20 V, are created by means of waves in the electron cyclotron (EC) range of frequencies. The microwaves are injected from the low-field side (LFS) during up to 800 ms in O-mode polarization using a magnetron source at $f_{\text{rf}}=2.45$ GHz and a truncated wave guide as an antenna. The microwave source is modulated at frequencies up to 20 kHz. The results shown in this paper were obtained in H plasmas, with 1.5 kW of power, and for four different values of the neutral gas pressure, equally spaced between $p_{\text{HI}} \approx 2 \times 10^{-3}$ mbar and $p_{\text{HI}} \approx 1.4 \times 10^{-6}$ mbar. The vertical field was set at 0.6 mT, approximately corresponding to the optimal value for particle confinement, and the toroidal field value such that the EC layer, where $f_{\text{rf}}=f_{\text{EC}}$ ($B_r=0.0875$ T), is about 12 cm off the plasma center, on the high-field side.

The plasma discharge is initiated by free electrons accelerated at the EC layer. Once a plasma is created, different resonances can exist. The kinetic model predicts resonant acceleration of electrons at the EC layer, where only a small fraction of the wave power is absorbed due to the small value of $k_L \rho_L$ ($\rho_L$ is the electron Larmor radius). The remaining fraction, reflected from the vacuum chamber walls at the high-field side, propagates with a mixed X- and O-mode character. At the upper hybrid (UH) layer, where $f_{\text{rf}}=f_{\text{UH}} \approx (f_{\text{EC}}+f_p^2)^{1/2}$, the X-mode encounters a fluid plasma resonance ($f_p$ is the plasma frequency). The wave $E$-field is strongly enhanced and can accelerate electrons up to energies well above the neutral gas ionization potential. A third, generally weaker contribution to the ionization rate comes from the tail of the thermal electron distribution; hence, with a broad spatial profile that reflects that of $T_e$ and $n_e$. The fraction of power absorbed at either resonance location and the relative weight of the ionization mechanisms are determined experimentally by measuring the plasma response to modulated microwave power. This leads to a reconstruction of the two-dimensional (2D) ionization profile, which constitutes a necessary input for the numerical simulations of the plasma dynamics. Parameters such as the vertical field, the neutral gas pressure, the location of the EC resonance and the amount of injected power can be varied to control the plasma profiles.

Sets of remotely controlled, movable electrostatic probes and analyzers are used to reconstruct the main plasma parameters over the poloidal section. A high degree of plasma reproducibility allows us to record high-resolution profiles of the different quantities by performing discrete, shot-by-shot radial scans of the measurement systems. In the example shown in Fig. 1, by radially moving and rotating an eight-tip Langmuir probe, a reconstruction of the $n_e$, $T_e$, and $V_p$ profiles was obtained, with measurement points spaced 1.8 cm vertically and between 3 cm and 1 cm radially. Notice the expanded scale in $T_e$, indicating a rather flat profile.

Thirty-three pairs of ac (capacitively) coupled, fixed Langmuir probes (1.3 mm between tips, 8 mm between pairs) installed around the plasma poloidally at the same toroidal location are used to measure the fluctuating component of the ion saturation current in the range 30 Hz–125 kHz, and to determine poloidal wave numbers $k_y$ up to 24 cm$^{-1}$. A hexagonal array of 86 Langmuir probes, named HEXTIP, is used to reconstruct the floating potential or ion saturation fluctuations and turbulent structures over the whole plasma cross section in a single plasma discharge, with a spatial resolution of 3.5 cm. The data presented in Sec. IV are recorded by a radially movable flux probe, which consists of four vertically separated tips (separation $=2.2$ mm), measuring ion saturation current, potential fluctuations and their relative phase. The data shown in this paper are acquired using two C-PCI based systems with 96 channels sampled at 250 kHz, with 16 bit resolution, and is organized using MDS-Plus tree structures.

In interpreting the ion saturation current signals from Langmuir probes, we neglect the influence of $T_e$ and $V_p$ variations. The validity of this approximation was checked on TORPEX by means of a boxcar-averaging technique. In particular, the density value obtained from a full analysis of the reconstructed I–V curves was shown to follow, within about 40%, that obtained from the ion saturation current sim-
dent that the instabilities occur primarily on the LFS, and in the region of a strong pressure gradient, where density and magnetic field gradients are colinear, corresponding to a maximum interchange drive. Note that the distribution of the potential fluctuations (not shown) appears similar to that of the density fluctuations, though less radially localized. The relative fluctuation level is quite high ($\bar{n}/n \leq 0.8$), and comparable with the potential fluctuations normalized to the electron temperature (see Fig. 9).

The power spectra of the density fluctuations for the four chosen values of the gas pressure, measured in the region of largest rms fluctuation levels, are shown in Fig. 3. A reduction in the amplitude, and a corresponding broadening of the coherent peaks can be noticed as the neutral pressure is increased. To identify the properties of the individual (coherent) modes, a systematic study of the spectra from all the probes distributed across the plasma was performed, and a histogram of the peak frequencies for all channels was made. The most frequent peaks are identified, regardless of their amplitude, and corresponding specific nonoverlapping spectral regions are defined for each peak. For each of these spectral regions, a 2D map of the average central frequency, width, and integrated amplitude of the peaks is generated. The result of this procedure is shown in Fig. 4 for two of the peaks that can be identified in the lowest neutral gas pressure discharges. In both cases amplitudes are large on the LFS and in the lower half of the cross section, but the location where the amplitude is maximum is different for the two different spectral regions. The frequency of the peaks in each spectral region remains practically constant over the whole cross section, with a variation of less than 10%, corresponding to the typical uncertainty in the peak fitting, significantly smaller than the width of the selected spectral region itself. These observations indicate that the modes are driven in the lower part of the profile, which acts as a source region. Then the strong macroscopic $E \times B$ flow created by the radial electric field convects the modes to the rest of the plasma.

The dispersion properties perpendicularly to the magnetic field are reconstructed using the fixed set of ac coupled probes distributed along the poloidal direction and applying a statistical method based on the two-point correlation technique. This method provides the conditional wave number and frequency spectrum, as shown in Fig. 5 for the source region. Consistently with the single point measurements of the spectrum (Fig. 3), the coherent character of the peaks apparent in the low pressure case tends to fade as the neutral pressure is increased. The slope in the graph for the low-frequency region ($f < 5$ kHz) is similar, indicating similar propagation speeds in the laboratory frame. For the spectral region around 4 kHz, the measured phase velocities in the vertical direction are, from the lowest to the highest pressure, 800, 650, 1250, and 2100 m/s (relative errors $\approx 30\%$). In all cases analyzed here, the observed direction of propagation is that of the $E \times B$ flow, i.e., upwards on the LFS, opposite to the electron diamagnetic drift. Therefore, for drift

III. FLUCTUATION MEASUREMENTS AND IDENTIFICATION OF INSTABILITIES

To characterize the relation between plasma conditions and the development of instabilities we have performed measurements of the 2D spatial distribution of the fluctuation amplitudes, their frequency and wave number spectra, dispersion relation, correlations and phase shifts between fluctuating density and potential. We study a series of plasmas fluctuating density and potential. We study a series of plasmas using a multiplicative factor, justifying the use of the latter as representative of the density dynamical behavior.25

Figure 2 shows the 2D profiles of the density and its fluctuations for the four values of neutral pressure, recorded by the HEXTIP probe and averaged over 500 ms. It is evident that the instabilities occur primarily on the LFS, and in the region of a strong pressure gradient, where density and magnetic field gradients are colinear, corresponding to a maximum interchange drive. Note that the distribution of the potential fluctuations (not shown) appears similar to that of the density fluctuations, though less radially localized. The relative fluctuation level is quite high ($\bar{n}/n \leq 0.8$), and comparable with the potential fluctuations normalized to the electron temperature (see Fig. 9).

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FIG. 1. (Color) Density, electron temperature, and plasma potential profiles (left), and the corresponding magnitude of density gradient, electron diamagnetic drift velocity ($v_d = T_e B / e B^2 L_n$, where $L_n$ the density gradient length scale) and $E \times B$ velocity (right) for $p_n = 2 \times 10^{-3}$ mbar. Note that $z$ is used for the vertical direction and $r$ for the radial one, with positive $r$ values corresponding to the LFS.
waves, the magnitude of the phase velocity should be the difference between the two. The quoted values are compatible with the data shown in Fig. 1, but the spatial variations and the error bars of both measurements prevent one from using this as a conclusive argument for the identification of the instabilities. Also note that the potential fluctuations in

FIG. 2. Distribution of density (top) and related rms value of the fluctuations up to 125 kHz (bottom). (a) $p_{H}=2 \times 10^{-5}$ mbar, (b) $p_{H}=6 \times 10^{-5}$ mbar, (c) $p_{H}=1 \times 10^{-4}$ mbar, and (d) $p_{H}=1.4 \times 10^{-4}$ mbar.
some cases are so large that the steady-state component of the $E \times B$ flow loses significance.

By applying the same analysis technique to signals from probe sensors aligned toroidally (almost parallel to the total magnetic field) and separated by 1.8 cm, and with a vertical size of about 2.5 mm, an estimate of the parallel dispersion relation is obtained (Fig. 6). Apart from the two low-frequency peaks, which have the largest amplitude at the probe location, on the midplane, at the lowest neutral gas pressure, all spectral components are characterized by a spectrum centered on $k$ values distinct from zero, consistent with the fluid model predictions of easier destabilization for higher parallel wave numbers for increasing collision frequency. Although the accuracy of the measurement is limited by the probe geometry and alignment errors, we can conclude that the magnitude of the perpendicular wave number is at least an order of magnitude larger than the parallel one, as expected for drift-interchange type instabilities.

The change in the character of the spectrum can be quantified in terms of the standard deviation of the $k_\|$ and $k_\perp$ spectra and, equivalently, its inverse, the correlation length. Both quantities are represented in Fig. 7 as a function of the gas pressure. First, it is clear that the perpendicular correlation lengths are much longer in the source region than at the top of the plasma, which can therefore be referred to as the turbulent region. Second, in both locations the perpendicular correlation length is reduced as the gas pressure is increased. Third, the correlation length in the parallel direction, measured at the midplane, scales with the neutral gas pressure in a similar way, and is about an order of magnitude longer than in the perpendicular direction.
In linear theory, it is often considered that the value of the phase between density and potential, reveals the nature of the electrostatic oscillation, for example discriminating between drift waves, Kelvin-Helmholtz and Rayleigh-Taylor instabilities. The phase spectrum measured in TORPEX for two neutral gas pressures is shown at the top of Fig. 8 as a function of the radial position. Although this is only a partial view of the 2D phase distribution over the whole cross section, it is clear that different spectral regions and radial locations are characterized by different phase relationships, and it would be misleading to try attributing a single value to the phase between density and potential.

IV. FLUCTUATION-INDUCED PARTICLE FLUX ACROSS THE MAGNETIC FIELD

The phase between density and potential influences the value of the turbulence-induced particle flux, whose time-average value along the radial direction is given by \(\langle \Gamma_{\text{radial}} \rangle = \langle \tilde{n} \tilde{v} \rangle\). Here, \(\tilde{n}\) and \(\tilde{v}\) indicate the fluctuating parts of the plasma density and the \(E\times B\) fluid velocity, \(\tilde{v} = \tilde{E}/B_0\). By expressing electric field fluctuations in terms of plasma potential fluctuations in Fourier space, \(E_z = -ik_z\tilde{\varphi}\), one obtains

\[
\Gamma_{\text{radial}} = \frac{2k_r(f)}{B_0} \gamma_{\tilde{n}\tilde{\varphi}}(f) \sin[\alpha_{\tilde{n}\tilde{\varphi}}(f)] \sqrt{P_{\tilde{n}\tilde{n}}(f)P_{\tilde{\varphi}\tilde{\varphi}}(f)}. \tag{1}
\]

The quantity \(\Gamma_{\text{radial}}/df\) represents the contribution to the flux from fluctuations in the frequency interval \((f, f+df)\). On TORPEX, Eq. (1) is used to determine \(\Gamma_{\text{radial}}\) from floating potential and density signals obtained using the flux probe described in Sec. II, and neglecting temperature fluctuations.

The contributions to the turbulent flux from the space and frequency resolved measurements are selected based on the spectral amplitudes, the relative coherence, the smoothness of the phase variation with frequency, and the wave number, which has to be in the range compatible with the probe geometry. The results for two neutral pressure values are shown in Fig. 8, along with the value of the flux integrated over all frequencies and the corresponding density profile. The frequency spectrum of the flux shows contributions for the different spectral modes that differ both in size and sign. For the low-pressure case, the flux is larger and is concentrated in the low-frequency range, where coherent peaks dominate, but contributions come from a larger spatial region. Conversely, in the higher pressure case, the flux is lower and results from the contribution of a broader spectral region but a narrower portion of the radial profile. In both cases, the sign of the total flux in the radial direction and on the midplane indicates an inward pinch. The left side of Fig. 9 shows a linear dependence of the integrated flux on the density fluctuation amplitude, and the same applies to potential fluctuations, as their amplitudes are proportional, as indicated by the right side of the same figure. It is remarkable that the integrated value of the radial flux on the midplane is compatible with the macroscopic profiles and confinement time, despite the complex spectral and spatial behavior.

V. STATISTICAL PROPERTIES OF THE FLUCTUATIONS

The local statistical properties of fluctuations naturally occurring in TORPEX plasmas can be expressed in terms of probability density functions (PDFs) and their moments. For
the plasma scenarios discussed above, measurements of the PDFs at different plasma locations, for the whole frequency range covered by the probe bandwidth yield significantly different results. Figure 10 (top) shows PDFs of the density fluctuations at four spatial points, for the four different values of the neutral gas pressure. The top left corresponds to the source region, characterized by a double-humped distribution, with strong, non-Gaussian density fluctuations for all cases. As the distance from the source region is increased (going counterclockwise, i.e., following the plasma convective velocity), the PDFs assume a more and more regular character. At the bottom of Fig. 10 we show the third- and fourth-order PDF moments (the skewness and kurtosis), for the same four positions, as a function of the neutral gas pressure. Significant departures from values characteristic of a Gaussian distribution can be noticed, but no clear overall trend can be clearly identified.

VI. STRUCTURES AND IMAGING

Probability distribution functions can provide information on the instabilities and turbulence and on their possible impact on plasma transport. However, this local description is difficult to interpret and cannot constrain univocally the theoretical models aiming to simulate the turbulence evolution. A full spatio-temporal imaging of the electrostatic fluctuations and turbulence needs to be undertaken.

FIG. 9. Dependence of the integrated fluctuation-induced flux on the density fluctuation amplitude (left), and relationship between density and potential fluctuation levels (right), from 0 to 15 kHz; i.e., including all spectral regions of interest.

FIG. 10. Top: PDFs of density fluctuations at four points around the plasma column, going counterclockwise from the source region (top left), at intervals of about 90° in poloidal angle, for the four gas pressures (from lower to higher: solid, dashed, dotted and dash-dotted lines). Bottom: Third- and fourth-order moments of the PDFs of density fluctuations at the four positions, as a function of the neutral gas pressure. Note that the kurtosis is referred to the Gaussian level, 3.
Two methods are routinely adopted on TORPEX. The conditional average sampling allows us to reconstruct the fluctuation structures with high spatial resolution from a large number of repetitive shots in which probes are moved across the plasma. A second method is adopted in this paper, based on direct measurements of potential and density fluctuations taken over a single discharge using the HEXTIP probe. A first example is shown in Fig. 11, which includes several frames from a discharge at the lowest neutral gas pressure. Structures other than a simple linear wave front form in the region of high instability levels and propagate in the plasma. Such a representation, which contains only a very small fraction of the data available for this discharge, is useful to obtain a qualitative idea on the turbulence dynamics, but provides limited quantitative information.

A necessary step to characterize the nature of the structures is to identify them as mathematical objects, and construct a set of observables from measurements of quantities representative of their dynamics, such as the center of mass, size, lifetime, and velocity. Due to the stochastic nature of the fluctuations, enough measurements of these observables for a sound statistical treatment should be available. In defining these observables it is important to take into account possible applications to the results of numerical codes, which would then be compared on their basis. In addition, the large amount of information to condense calls for stable and computationally efficient algorithms.

The following procedure is followed here. HEXTIP data are first extrapolated to the whole poloidal cross section, assuming zero fluctuations at the wall, then processed using a contouring algorithm. A structure (or blob) is delimited by a bounding contour, defined by a minimum level of density fluctuation, chosen here as the standard deviation, calculated from the concatenation of all signals, for the density fluctuations. Integrations over the structures, for example to determine their center of mass, are performed using linear tetrahedral finite elements, which provides a satisfactory stability of the results against effects due to the finite spatial resolution. The trajectories of the center of mass of the structure can then be reconstructed by comparing consecutive time frames. To represent their statistical distribution, we divide the cross section into a rectangular grid and count the number of trajectories that traverse each bin, where we also determine the average trajectory velocity. Figure 12 shows the statistics of the presence of blob trajectories over the poloidal cross section, for two pressure values. Only orbits that last for longer than 200 μs are considered here. The data are prefiltered in the frequency bands corresponding to the two modes observed on Fig. 4. By looking directly at the trajectories, one can infer that, for each mode, the blobs originate in the region of large amplitude, but propagate well beyond it. Superimposed on the color plot, the arrows represent for each bin the speed and direction of the motion of the center of mass of the structures. Aspects of the trajectory patterns for the two cases are similar to the reconstructed $E \times B$ flow field, but significant differences can be found between the motion of trajectories originating from each spectral region.

To complete this information, the statistics of the size of the structures is evaluated, both in terms of the area occupied by the bounding contour and of the number of particles per parallel unit length simultaneously contributing to it, divided by the area. Note that the latter observable is less sensitive to the choice of the minimum level, from which the bounding contour is determined. The histograms of these quantities generated for the same data as shown in Fig. 12 indicate a decrease in the probability of having large size structures as the gas pressure is increased, in agreement with a reduction of the correlation length shown in Fig. 7.

VII. CONCLUSIONS

In summary, we observe strong drift-interchange electrostatic instabilities in the TORPEX toroidal plasma, propagating in the laboratory frame primarily according to the $E \times B$ plasma flow, starting from a region of large gradients...
and unfavorable magnetic field curvature. The coherent waves driven in this region can be recognized as low-amplitude peaks at exactly the same frequency over the whole plasma cross section, where they are convected by the plasma flow. Local dispersion relations, and a ratio of normalized density to potential fluctuations of order unity are compatible with drift instabilities. The measured phase relationship between perturbed density and potential shows a complex behavior, with no indication of extended radial eigenmodes. In regions away from the source a more turbulent character is observed, with shorter correlation lengths. As the charged particle-neutrality collisionality is increased, a more turbulent state, with broader wave number spectra, characterizes all locations in the plasma. The fluctuation-induced particle flux is generated in more spatially localized regions and decreases as the neutral gas pressure is increased, corresponding to lower fluctuation levels.

A comparison with a model that could reproduce the macroscopic spatio-temporal features of the turbulence can only be meaningful if observables are defined that are representative of the turbulent structure dynamics and can be measured in the experiment and evaluated in the numerical code outputs. A first attempt at defining such quantities and at measuring them as a function of experimental conditions was conducted. The distribution of trajectories, speeds and directions, of spatially extended structures is reconstructed for different cases, and indicates that the trajectories evolve along with the $E \times B$ flow, starting from the region of the strong instability source. The distribution of the sizes confirms that shorter correlation lengths correspond to smaller structures.

New diagnostic tools will be developed in TORPEX to improve the coverage, the sensitivity, and the resolution of the field and fluctuation measurements, and to reduce the perturbation caused on the plasma, including a multichannel fast camera. On the theory side, activities to adapt state-of-the-art fluid codes to the TORPEX geometry are under way, with particular attention given to the introduction of the experimentally determined plasma source profile, and to a correct treatment of the parallel dynamics, whose influence can be experimentally verified in the experiment by varying the vertical magnetic field value.

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