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Three-dimensional structures in the torsatron TJ-K

N. Mahdizadeh^{§†}, F. Greiner [†], T. Happel[†], M. Ramisch[†], U. Stroth[‡]

[†] IEAP, University of Kiel, Germany

[‡] IPF, University of Stuttgart, Germany

Abstract. The three-dimensional structure of drift wave turbulence is studied in the low temperature plasma of the torsatron TJ-K. Previous 2D investigations of plasma density and floating potential fluctuations in the poloidal plane have shown that drift waves play the dominant role for the formation of coherent structures and radial transport [U. Stroth, Phys. Plasma, **11**, 2558(2004)]. The observed structures are quasi-coherent and show a scaling with the drift scale $\rho_s = c_s/\omega_{ci}$. The distinguished characteristic of drift waves is the dynamic parallel to the magnetic field, i.e. $k_{\parallel} \neq 0$. Therefore a detailed understanding requires fully three dimensional investigations. A combination of a 2D-movable probe and a poloidal 8×8 matrix of electrostatic probes is used to investigate the parallel dynamics in TJ-K. A heuristic model is proposed, which shows that the parallel dynamic in TJ-K is described by the occurrence of large, spatially localized coherent structures with drift wave dynamics.

1. Introduction

In most cases plasma turbulence is closely related to the occurrence of large scale structures or quasi coherent modes. The relevancy of these modes for plasma transport strongly depends on the cross-phases γ between density and potential fluctuations. If the structures are interchange modes, the phase is nearly $\pi/2$, whereas for drift dynamics it is close to zero. Detailed 2D Investigations of the plasma dynamics in the TJ-K torsatron have shown that turbulence and transport are dominated by drift waves [1, 2]. The low temperature plasma of TJ-K is dimensionally similar to the edge of a fusion plasmas, and has the unique feature that probe measurements can be done over the whole plasma cross section. Standard two probe techniques to extract structures from the density and potential fluctuations are cross-correlation (CCF) and conditional averaging (CA). To get information of the plasma on the full poloidal cross section only two simultaneously acquired time series of a fixed reference probe and a probe moved to each position on the poloidal cross section are needed. However, the extracted information about coherent structures is time averaged and the

[§] (zadeh@physik.uni-kiel.de)

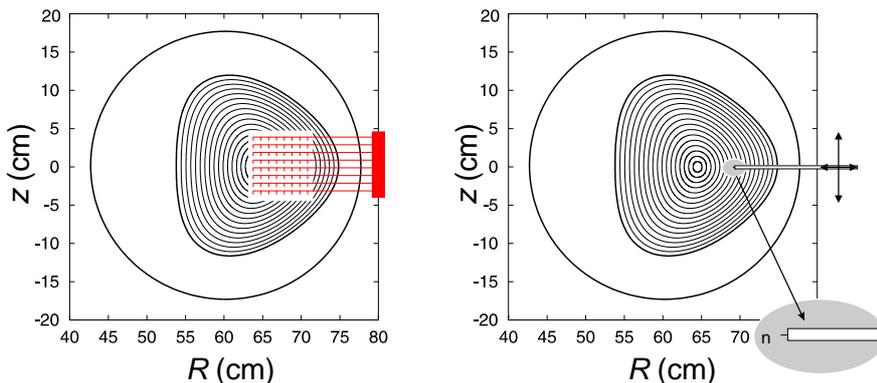


Figure 1. Left: Sketch of Probe Matrix, the probe separation is 1 cm. Right: Sketch of the 2D-movable probe system, the probes can be moved over the whole poloidal cross section with a resolution of 1mm. Both figures are underlaid with the contours of the calculated magnetic flux surfaces.

ergodic theorem has to be fulfilled. In contrast to two probe measurements multi probe measurements can be used to get simultaneously spatial and time resolved measurements of the plasma dynamics. If probes are arranged in two dimensions, enhanced analysis methods can be used and ambiguities of 1D-probe arrays can be avoided.

In this contribution we present a study of the three dimensional properties of the drift wave dynamics in the low temperature plasma of the TJ-K torsatron. After a short introduction to the device and the diagnostics system, a heuristic model for the distinction of drift waves and coherent structures with drift dynamics in three dimensions is presented and applied to data of the TJ-K.

2. Experimental setup and diagnostics

Experiments are carried out in the torsatron TJ-K ($l = 1$, $m = 6$) which has a major radius of 0.6 m and a minor radius of 0.1 m [3, 4]. The rotational transform is about 1/3. Due to plasma generation by electron-cyclotron-resonance heating (ECRH) at 2.45 GHz, the nominal magnetic field is limited to 70–100 mT. Details on the operation parameters can be found in Refs. [5, 1]. In the present experiments the working gases were hydrogen, deuterium, helium, neon and argon at a neutral gas pressure of 3×10^{-5} mbar and a heating power of 2 kW. The electron temperature was $T_e \simeq 10$ eV and the line-average density about $1.2 \times 10^{17} \text{m}^{-3}$. Ions are cold.

The three-dimensional structure of turbulence is investigated by an array of 8×8 Langmuir probes (named matrix in the following) and a 2D-movable probe system (named reference probe in the following). The matrix has a full size of 8×8 cm, i.e. the distance between neighboured probes is 1 cm in both vertical and horizontal direction. The reference probe can be moved over the whole poloidal cross section with a spatial resolution of 1 mm. Figure 1 shows a sketch of the

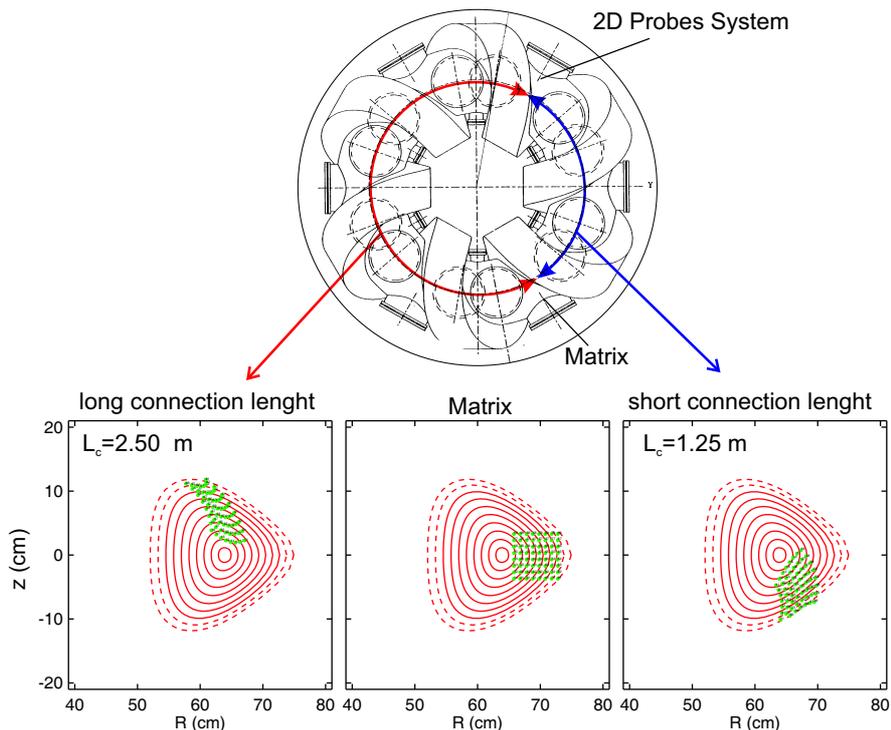


Figure 2. Top: Sketch of the TJ-K showing the location of the Matrix and the reference probe and the long and the short connection between them. Bottom: Mapping of the probes on the matrix counterclockwise to the reference probe (left) and clockwise to the reference probe (right).

matrix and the reference probe. Both probes are located at equivalent toroidal positions 120 degree separated, i. e. the magnetic flux surfaces have the same triangular contour. This contour is underlayed to Figure 1. The details of the 8×8 array probes and 2D-movable probes can be found in [6, 7]. The distance along the magnetic field line connecting the 2D-movable reference probe and the matrix probes is referred to as connection length. Looking onto the device from top (see top of Figure 2) the clockwise distance along the magnetic field lines connecting the reference probe and the matrix is referred to as short connection (1.25 m) and the counterclockwise distance is referred to as long connection (2.5 m). The investigation of 3D dynamics of drift waves requires detailed knowledge of the mapping of the magnetic field lines between reference and matrix position for both long and short connection. The numerical calculations are done with the field line tracing code [8]. It is verified with a thermionic micro discharge. To do this, a small hot cathode is fixed on the reference probe and a voltage is applied between matrix and reference probe. A localised discharge can be established between the probes, when a magnetic field line exactly connects them, i.e. if the reference probe is moved around until this discharge establishes. In this way the magnetic mapping can be verified. Figure 2 shows the calculation of the magnetic mapping from the matrix (center) counterclockwise to the reference probe (long connection, left) and clockwise to the reference probe (short connection, right). If

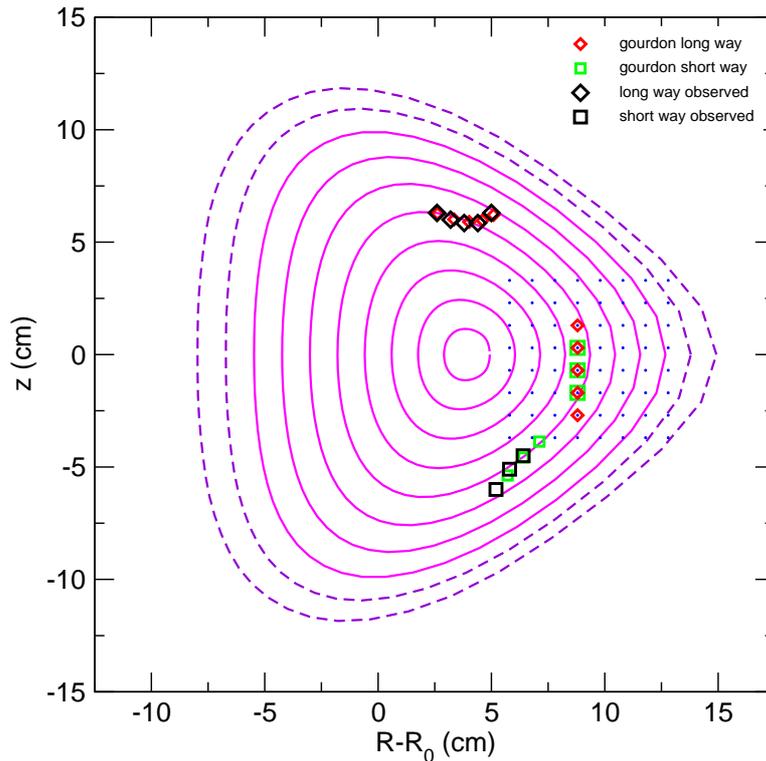


Figure 3. Comparison of field line calculations (colored symbols) and experimental verification with a thermionic micro discharge (black symbols), for both long (diamonds) and short connection (squares).

one follows the magnetic mapping of a probe column of the matrix along the long connection this column is twisted counterclockwise into a row at the position of the reference probe. The effect is comparable for the short connection. However, the twisting is smaller (45 degree) in clockwise direction. The comparison of the calculations with the experimental data (Figure 3) shows excellent agreement for the long connection, for the short connection slightly deviations are observed. For the following analysis, the experimental mapping points are used.

3. Experiments on parallel dynamic in TJ-K

For all gases long time series of ion saturation current fluctuations of the reference probe and the whole matrix were acquired for the mapping points presented in Figure 3. The parallel dynamics is then extracted from the time series by means of cross-correlation technique, i.e. the correlation function of the reference probe data with all probes of the matrix is computed. As result a series of spatial-temporal snapshots of the averaged structure dynamics is generated. Figure 4 shows a section of this sequence around zero time for the long connection in hydrogen. A structure moves with electron diamagnetic speed v_{dia} from the upper left to the lower left corner, passing the magnetic field line connecting to the reference probe and the matrix (marked with a cross in Figure 4). Detailed

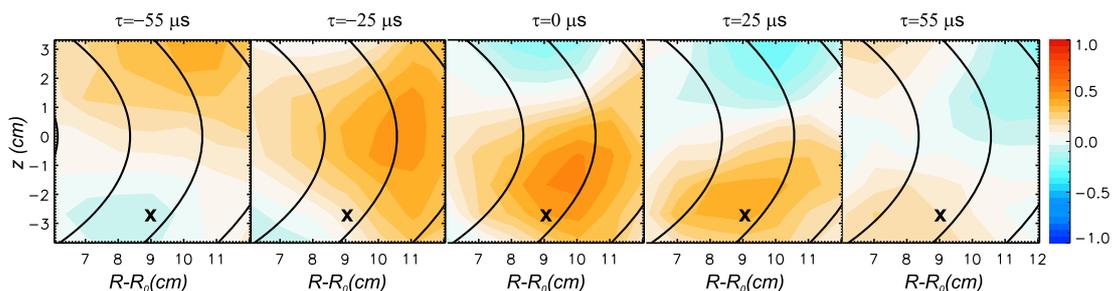


Figure 4. CCF-visualisation of structures moving cross the matrix for a discharge in hydrogen for the long connection. The black cross marks the position of the intersection of the magnetic field line the reference probe is positioned on.

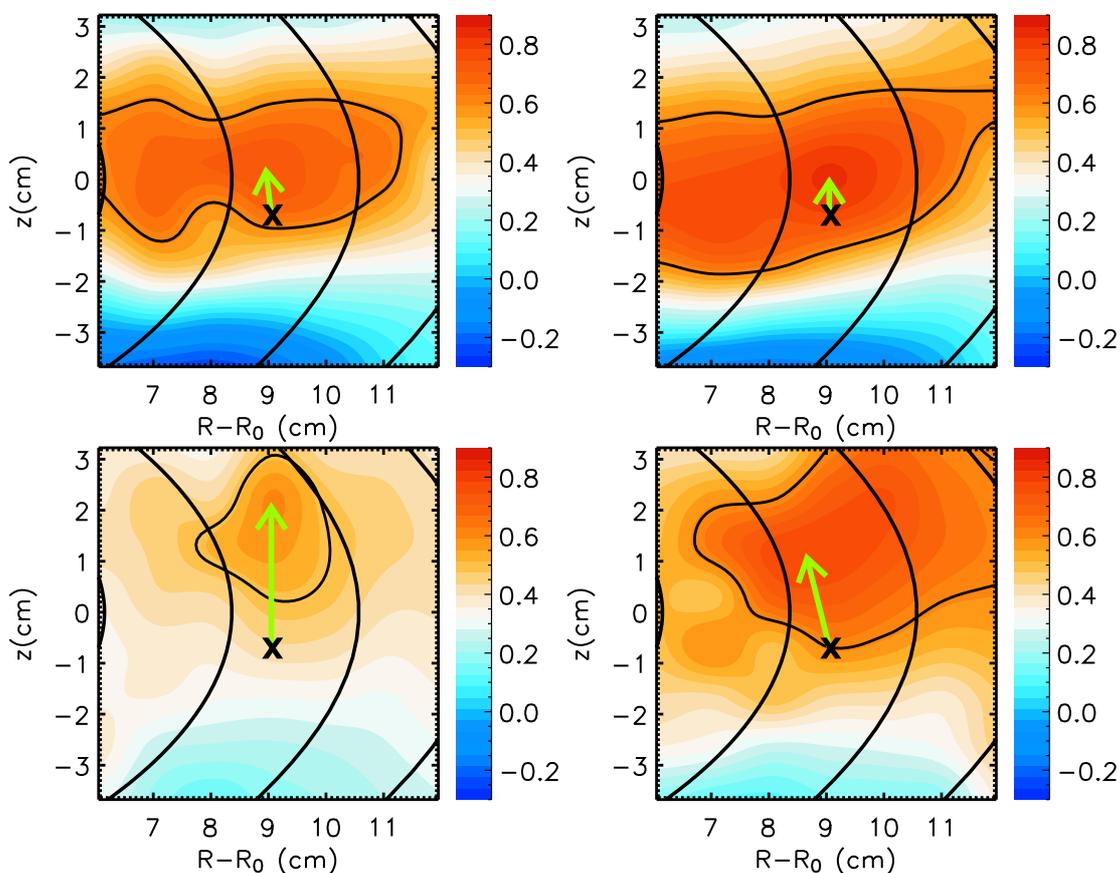


Figure 5. Spatial cross correlation for helium (top) and neon (bottom). The structure at the time delay of maximum correlation is shown for long (left) and short (right) connection length. The black cross marks the intersection point of the magnetic field line, the arrow points to the position of maximum correlation. The displacement is due to the parallel dynamics.

analysis of the absolute value of the correlation for each snapshot on the matrix reveals that the maximum correlation, i.e. the direct connection between matrix and reference probe, is displaced from the magnetic field line. This is shown for helium and neon for both connection lengths in Figure 5.

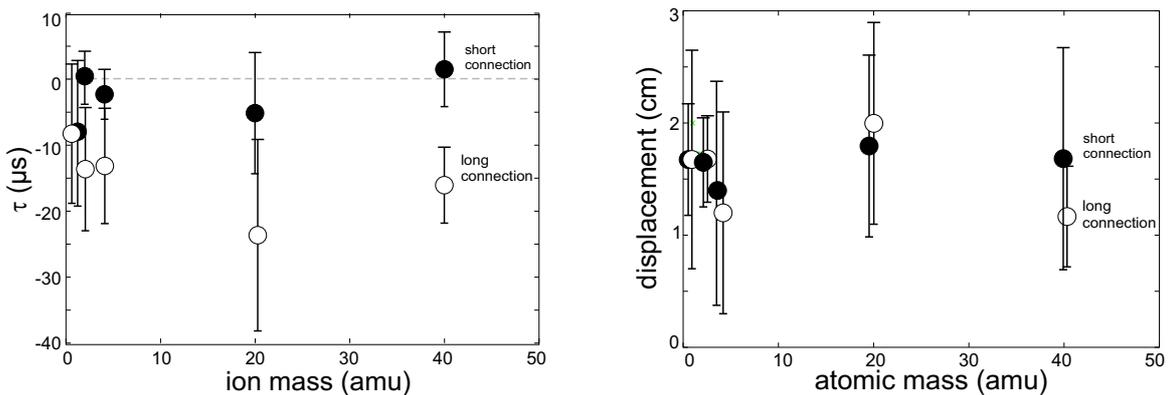


Figure 6. Left: Time delay between maximum correlation of reference probe and matrix for hydrogen, deuterium, helium, neon and argon. Right: Absolute value of the displacement. The error bars depict the standard deviation of all vertical positions (marked in Figure 3) and up to three shots.

As a first result, this means that the dynamics in TJ-K is truly three-dimensional, i.e. the parallel displacement of structures is affected by drift dynamics. This is consistent with the results from 2D investigations, where also drift dynamics were found. In addition, the observed time delay (maximum correlation is not found at zero time lag) can be used to get insight into the parallel dynamics. Figure 6 presents a compilation of the observed displacement for all experiments, i.e. averaged displacements for all measured vertical positions of the matrix and all used gases. In the following we present a heuristic model to interpret this results.

4. Heuristic model

If 3D dynamics are analyzed by means of 1D probe arrays, ambiguities are unavoidable, i.e. the wavefront of a drift mode can not be distinguished from spatial localized structures. If 2D-probes are used, this ambiguity can be nullified. We present a heuristic model in the style of that given by Thomsen [9] for the interpretation of fluctuation data of the SOL in the JET tokamak. Because drift waves have a parallel wavelength the wavefront of a drift mode is moving with a small angle to the magnetic field. This situation is shown, somewhat overdone, in the upper part of Figure 7. It is assumed that at $t = 0$ the reference probe and one probe of the matrix are on the same magnetic field line. To get a picture what is going on, we imagine that we have two matrices, one to the left (long connection L'_C) and one to the right (short connection L_C). In the figure, only a (1D) column of the matrices is shown, it should be kept in mind that for the analysis of the displacement, radial and vertical information is necessary, i.e. in practise 2D-matrices of probes are needed to find the intersection point of the structure in the poloidal cross section. The wavefront swishes to the reference probe, the matrix at L'_C and the matrix at L_C at $t = 0$ with a parallel displacement of D'_\perp

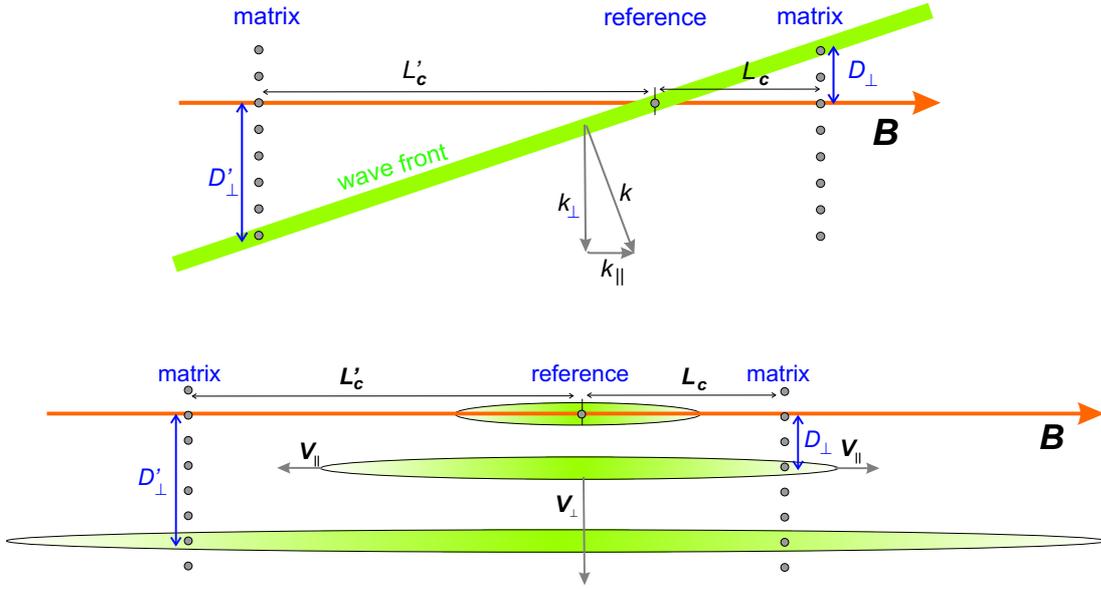


Figure 7. Top: The maximum value of a moving wavefront reaches the reference probe and matrices toroidally displaced to the left and the right at zero time lag. Bottom: A parallel elongating structure with drift dynamics reaches these matrices at non zero time lag. For simplification only the column of the matrix targeted by the magnetic field line from the reference probe is shown, the rows of the matrix point out of the paper plane.

and D_\perp and zero time lag. This means that the finger prints of a drift wave are a converse displacement on different directions from the reference probe with zero time lag to the reference probe. However, due to different magnetic shear and absolute value of the magnetic field no simple relation between D'_\perp and D_\perp can be assumed. In contrast to a wavefront the lower part of Figure 7 depicts what happens when a spatial localized coherent structure passes the reference probe and the two matrices. Imagine a structure passing the reference probe at $t = 0$ with a parallel localization smaller than $L'_c + L_c$. Assume that the structure elongates along the magnetic field line with v_\parallel and moves across the magnetic field with v_\perp . In contrast to a wavefront no structures are detected at the matrices at $t = 0$. Instead, the structure passes the matrix at L_c with $|t| < |t'|$, where t' is the time, when the structure passes the matrix at L'_c . In addition a displacement of the structure is observed. However, the displacement has to be in the same direction for both L'_c and L_c . Again, the absolute value of the displacement depends on the magnetic shear and the absolute value of the magnetic field on the way from the reference probe to L'_c and L_c . Table 1 summarizes, how drift waves and structures with drift dynamics can be distinguished by means of time delay and spatial displacement.

| drift dynamics | detection at time delay | sign of displacement |
|----------------|-------------------------|----------------------|
| mode | 0 | inverse |
| structure | $\neq 0$ | equal |

Table 1. Difference between drift modes and structures with drift dynamics by means of parallel displacement and time delay. 'detection at time delay' is the time between detection at the reference probe and the toroidal displaced matrix and 'sign of displacement' is the sign between the displacements to the left and the right of the reference probe. See text for details.

5. Discussion and Conclusion

Using the above mentioned criteria on the data measured in TJ-K (compiled in Figure 6), it immediately follows that parallel dynamics of spatially located coherent structures is observed. Although the error bars are fairly large, the CCF-analysis gives a significant time delay between reference probe and occurrence of maximum correlation on the matrix. Consistent with this, the time delay is larger for the long connection length. In addition the displacement is into the same direction for both connections. The absolute value of the displacement is nearly the same for long and short connection. Beside the large error and the fact that the resolution of the matrix is only 1 cm, this can be attributed to the fact that the connecting field line for the short connection is located at the low field side (LFS) whereas for the long connection the field line is located at the high field side for the main part of the distance. From investigation of the 2D-dynamics it is known, that in consistence with drift dynamics, the structures propagate with electron diamagnetic velocity v_{dia} in the direction perpendicular to the magnetic field. This immediately implies, that the parallel displacement of the structure strongly depends on the averaged magnetic field on the way from reference probe to matrix. Compared to the short connection, the displacement for the long connection should be smaller than a linear dependency on time would predict. This is again consistent with the findings of our experiments. However, a detailed comparison requires calculations of the averaged magnetic field on the way of the structures, which is under way. From the known perpendicular displacement and connection length the perpendicular and parallel velocity of the structure can be estimated. Whereas the perpendicular velocity gives indeed the v_{dia} within a factor of two, the parallel velocity is much larger than sound speed, which is the maximum propagation velocity for density depressions parallel to the magnetic field. Measurements using floating potential fluctuations are necessary to investigate this further. Nevertheless this investigation enhances the results given in [10, 5, 2, 11, 1, 6]. The dynamics in TJ-K is 3D. In the direction parallel to the magnetic field the dynamics is dominated by large, spatially localized coherent structures with drift wave dynamics.

Acknowledgments

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