Configuration of Flows in a Cylindrical Plasma Device*)

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Ion flow is studied in the cylindrical magnetized Argon plasma of the PANTA device using several experimental methods. Time delay estimation technique (TDE) is used to measure the azimuthal propagation of density fluctuations between two electrostatic probes. Ion flux is also studied in azimuthal and axial direction using a newly installed Mach probe. TDE shows velocity profiles qualitatively consistent with expected drift wave propagation and $E \times B$ rotation. The Mach probe shows a maximum azimuthal flow and an axial flow shear close to the maximum density gradient and maximum fluctuation position. Striking differences exist in the detected axial ion flows depending on the discharge parameters. In high neutral pressure conditions reversal of axial ion flow was detected in the outer part of the plasma column. Temporal evolution of flows and fluctuations are compared as a first step to assess interplay between plasma turbulence and flows in the radial, axial and azimuthal directions.

Keywords: linear magnetized plasma, cross-field flux, ion flow, Mach probe, time delay estimation

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1. Introduction

The investigation of velocity fields in turbulent magnetized plasmas is a crucial issue for the understanding of edge plasma losses, plasma-wall interactions and impurity transport. The detailed study of flows is a challenging task, especially in bigger devices, due to the complexity of the plasma configuration and the limitations for diagnostics. Laboratory plasma devices with their high reproducibility and easier experimental access are used since many years for the investigation of fundamental processes of plasma turbulence and turbulent transport [1, 2]. Remarkably few studies however assess the total particle balance in small devices including the axial flow components. Indeed, turbulence itself is usually considered to be close to two-dimensional and the axial flow is expected to obey diffusion from source to end plate. Electric fields in the axial direction in the device have been studied for specific discharges (e.g. [3]) but are not measured routinely. However, recently new fundamental questions concerning the particle flow configuration arise. Radial cross-field plasma transport has been studied in many devices and some discharge regimes showed bursty transport [4] or inwards transport [5] not compatible with the transport expected for drift wave turbulence. Especially in that cases, flows in the axial direction could contribute significantly to the overall flow configuration. Similarly, an interplay of axial and poloidal components has been suggested as an origin of intrinsic toroidal flux in larger devices. That rotation could be influenced by radial particle flux via the turbulent Reynold's stress. In this contribution, we present flow measurements in the cylindrical device PANTA. The ion flow is assessed using Mach probes and applying time delay estimation (TDE) on time series recorded with electrostatic probe tips. In the first part of this contribution, the experimental device PANTA is presented and the design and calibration of a compact Mach probe is detailed. The principle of flow measurement is explained and results of mean flow measurements by Mach probes and TDE are shown for two different regimes. Observations about the temporal evolution of flux are given before the results are summarized.

2. Experimental Setup and Mach Probe Design

This experimental study has been carried out on the Plasma Assembly for Nonlinear Turbulence Analysis, PANTA. The device consists of a cylindrical vacuum vessel with a length of 4.05 m and a diameter of 45.7 cm. A helicon discharge is created by injection of a 7 MHz ra-

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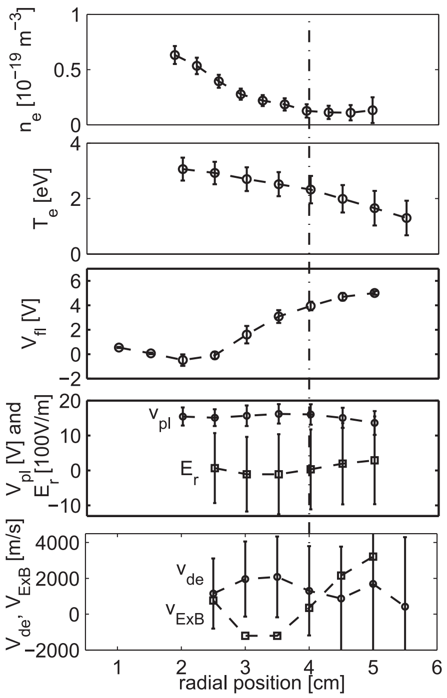

Fig. 1 Typical discharge profiles of plasma with a neutral argon pressure of 0.1 Pa.

dio frequency wave through a double-loop antenna with a 3 kW power source. The diameter of the antenna loop is 10 cm. The steepest density gradient of the plasma column is located between 2 cm and 4 cm from the column center. Magnetic field coils surrounding the plasma vessel create an axial field of 0.09 T. Argon gas is filled in the device through a mass-flow controller and stable discharges are obtained for neutral pressures between 0.1 Pa and 0.4 Pa. The vessel is continuously pumped by four turbo-molecular pumps. The two most powerful pumps, which account for 80% of exhaust flow, are placed near the end plate. Depending on neutral gas pressure and magnetic field, different discharge regimes can be obtained. Similar to observations in a previous cylindrical device [6], fluctuations are composed of drift waves and nonlinearly driven fluctuations. Illustrations of the device can be found in [7]. Profiles of plasma density n_e, electron temperature T_e and floating potential V_{fl} shown in Fig. 1 have been measured with a radial moveable double probe. Plasma potential has been computed as $V_{pl} = V_{fl} + (k_B T_e/2e)\ln(\pi m_i/2m_e) = V_{fl} + 5.2T_e$ and gives the radial electric field as well as the expected $E \times B$ rotation velocity. Electron diamagnetic drift velocity $\upsilon_{de} = -(k_B T_e/eB)(\nabla n/n)$ corresponds to the phase velocity of drift waves in a first order approximation and is computed from density and temperature profiles. Error bars are evaluated from the standard deviation of parameters obtained for several shots. Error bars for $E \times B$ rotation would exceed the plot axis due to the important impact of errors in the temperature and correspondingly in the electric field.

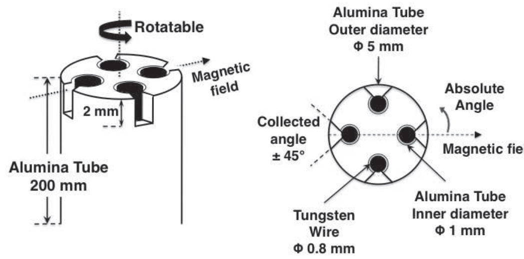

Fig. 2 Schematic of the Mach probe tip.

In order to measure ion flows, a compact Mach probe has been constructed. The Mach probe consists of an insulating alumina tube containing four tungsten tips arranged in a square in order to form two perpendicular pairs of Mach probes. One pair is used to assess the axial, or parallel, ion flow while the second pair measures the azimuthal, or perpendicular, flow. Figure 2 shows a schematic of the probe tip. The probe is mounted on a radially moveable vacuum pass-through. The tips are operated in ion saturation mode with a bias of −90 V. Prior to flow studies, the radial position of the Mach probe is calibrated with respect to a reference probe at the same azimuthal angle and known radial position by searching for the radial position with maximum cross-correlation between both probes. The alignment along magnetic field lines has to be determined carefully. This is not straightforward in the case of drift wave turbulence, as fluctuations have an axial wavelength and therefore the density structures have a helical twist with respect to the parallel direction. Axial alignment has been achieved by placing the probe in the center of the plasma column, where purely axial flow is expected. The probe shaft is then rotated and the angle of maximal flow is identified as the parallel direction. Finally, the measured ion fluxes have to be calibrated with respect to the probes' areas. To this end, measurements of collected ion current are taken for a complete turn of the probe. The mean collected current are used to compute a calibration factor. The angular plots of the currents can also be used to check that the probe holder is not twisted in the radial and parallel plane.

3. Flow Measurement Principle

Mach probes measure the difference in ion collection between a probe facing upstream and a probe facing downstream [8]. Although the global result that collection facing upstream should be larger than on the other side is rather intuitive, the deduction of an exact relation between that asymmetry and the flow velocity requires advanced understanding of ion dynamics in the sheath and pre-sheath region of the probe. Especially for weakly magnetized plasmas, where the ion Larmor radius exceeds the probe dimensions while the Debye length remains much smaller than the probe size, numerical factors in the relation are still a matter of debate (see for example [9] and responses).

The model of Hudis and Lidsky [10] gives a simple solution popular with experimentalists. Following [11], the Mach number M and flow velocities v presented here were computed as follows:

$$M = \frac{v}{c_s} = \sqrt{\frac{T_e}{2T_i}}\,\frac{\langle I^+\rangle - \langle I^-\rangle}{\langle I^+\rangle + \langle I^-\rangle}, \qquad (1)$$

where $\langle I^+\rangle$ and $\langle I^-\rangle$ are the time averaged ion saturation currents collected by the upstream and downstream facing probes respectively, T_i and T_e are the ion and electron temperatures in eV and $c_s = \sqrt{T_e/m_i}$ is the ion sound velocity. Measurements by triple probe and conditional sampled single probe indicated electron temperatures about 1 eV [7] and accordingly, $T_e \simeq 1.5\,\text{eV}$ has been used here. The ion temperature has not been measured yet and is assumed to be $T_i \simeq 0.1 - 0.5\,\text{eV}$. Although there may be significant errors on the estimated temperatures, the flow velocity has only a square root dependence on these values. Other issues, like the used ion collection model, may have bigger effects on computed Mach numbers [12]. Moreover, Mach numbers are usually overestimated compared to Light Induced Fluorescence measurements [13]. As different models can show large discrepancies for quantitative studies, interpretation of absolute flow velocities is in general difficult.

Another method for estimating velocities is the Time Delay Estimation technique (TDE). Time series of fluctuations are taken at two spatial locations. Cross-correlation of the two time series gives the travelling time of fluctuations. Knowing the distance between the two positions, the propagation velocity of fluctuations can then be deduced. In this study, rotation velocities were obtained by applying the TDE method to ion saturation current data from a radially moveable three tip probe with an azimuthal tip distance of 5 mm. The TDE method detects propagation of a perturbation in the laboratory frame, i.e. it can not give phase velocities but only the group velocities of fluctuations, possibly including background flows, such as the $E \times B$ rotation in azimuthal direction [14]. Detection and computation of different velocity components can be summarized as follows:

$$\begin{array}{lcll}
\mathrm{v}_{\mathrm{TDE}} & = & \mathrm{v}_{\mathrm{de}} & + \mathrm{v}_{E_r\times B} + \mathrm{v}_{\mathrm{others}} \\
\mathrm{v}_{\mathrm{Mach}} & = & & \mathrm{v}_{E_r\times B} + \mathrm{v}_{\mathrm{others}} \\
\text{Profiles} & \rightarrow & \mathrm{v}_{\mathrm{de}} & \\
\text{Profiles} & \rightarrow & & \mathrm{v}_{E_r\times B}
\end{array}$$

4. Mean Flow Measurements

Mean ion flow is given in Figs. 3 and 4 for neutral pressures of 0.1 Pa and 0.4 Pa. Looking first at the 0.1 Pa case, perpendicular velocity profiles obtained with the Mach probe and TDE method are similar at the position where instabilities are driven, around 3 cm. They show a significant difference toward the edge, where flux detected by the Mach probe decrease but the TDE velocity increases, following the rigid-body rotation of the drift wave structure. The TDE results are in agreement with the profile shape predicted by v_{de} and $v_{E\times B}$ from Fig. 1. At 3 cm, the axial flow measured with the Mach probe is strongly sheared. Maximum Mach numbers in perpendicular and axial direction are about 0.25, respectively 0.4, which is in agreement with Mach numbers between 0.3 and 0.6 found in a similar linear device with similar experimental conditions [15]. In the 0.4 Pa case, Mach probe measurements show similar qualitative features as in the lower pressure case; Axial flow shear and maximum perpendicular flow are measured around 3.5 cm. However, the axial flow is reversed at outer radii, i.e. a back-flow is detected from the end plate towards the source. The TDE methods detects a slower perpendicular propagation, which is consistent with a slower drift wave velocity, indicated by the plasma profiles (not shown here).

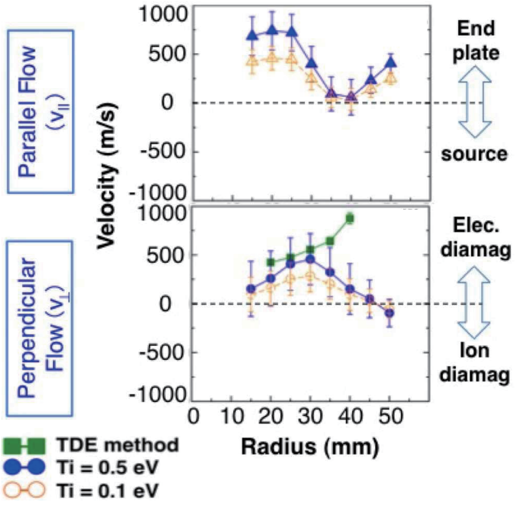

Fig. 3 Parallel and perpendicular flows measured with the Mach probe (assuming two different ion temperatures) and the TDE method for a neutral pressure of 0.1 Pa.

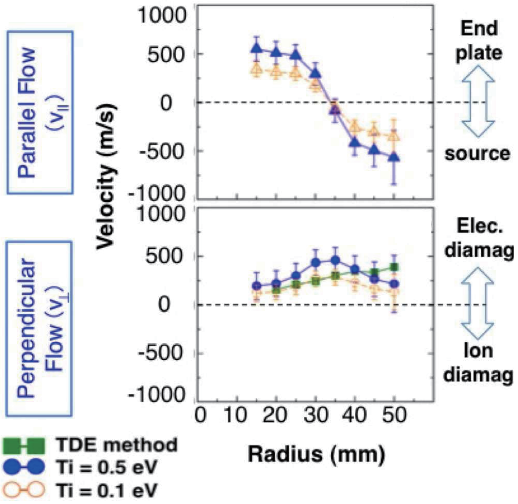

Fig. 4 Parallel and perpendicular flows for a neutral pressure of 0.4 Pa.

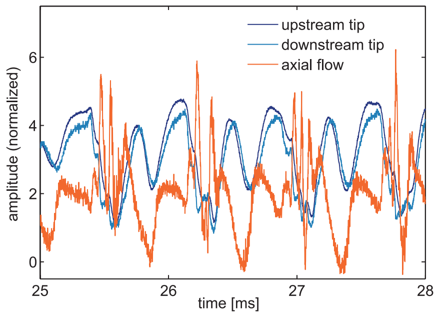

Fig. 5 Ion saturation currents and axial flow measured at r = 4 cm with a neutral pressure of 0.4 Pa.

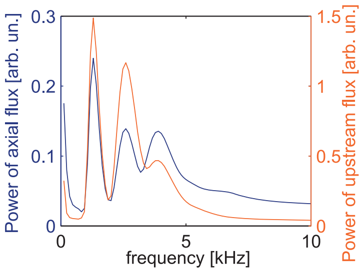

Fig. 6 Power spectra of axial flux and density fluctuations.

5. Time Evolution of Flow

In principle, the ratio of collected ion saturation currents can be used to study flow velocity resolved in time and space. The time evolution of flow velocity can be followed by replacing the mean ion saturation currents $\langle I^+\rangle$ and $\langle I^-\rangle$ in equation1 by the corresponding instantaneous values. Figure 5 shows the time traces of ion saturation current on the two tips of the Mach probe and the obtained axial velocity in the shear layer with the 0.4 Pa discharge condition. During each period of 1 ms, the ion saturation current has two peaks of different shape and height. The flow fluctuates together with the ion saturation current but behaves differently for the two peaks. While flows are finite during the main peak, they drop almost to zero during the smaller peak. Figure 6 shows the power spectra of ion saturation current and axial flow. The same frequency components appear in both spectra but the flow has stronger harmonics and even the third harmonic is visible in this linear plot. Indeed, high frequency components can be seen in the flow time trace when the large density peak decreases. Those components do not contribute prominently to the averaged flow but influence the fluctuation spectrum.

6. Summary and Outlook

Ion velocities were investigated in a linear device using different methods and several discharge conditions. Large discrepancy are found between the velocities obtained with Mach probe and the TDE method especially at the edge of the plasma column. The TDE velocity is determined by the drift wave propagation velocity at the excitation radius of the dominant fluctuations, together with $E\times B$ rotation predicted by plasma profiles. In contrast to this, Mach probe measurements don't detect wave propagation but give a local measurement of particle flow. The Mach probe velocity profiles show an axial flow shear and perpendicular flow maximum where turbulent fluctuations are strong. The absolute values of flow velocities may change with the calibration factor used for Mach probe measurements. The qualitative findings and especially the observation of the reversed axial flow detected at outer radii for high neutral pressure conditions are however independent of the chosen formula. To understand the configuration of particle sources and sinks in the device, further measurements are needed, particularly along the magnetic axis. Moreover, indications of an interaction between parallel dynamics and radial transport in another linear device [16] show the importance of detailed studies of dynamic evolution of flow and particle transport in multiple dimensions. As a first step, temporal evolution and frequency spectrum of axial flow have been compared to plasma fluctuations.

Acknowledgments

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