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# Nonlinear dynamics of shear flows and plasma rotation in a simple laboratory plasma system

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**Abstract**
Nonlinear turbulent-shear flow interactions are directly measured in a cylindrical helicon plasma device and found to lead to the development of an azimuthally symmetric radially sheared azimuthal flow by the action of a turbulent Reynolds stress which transfers kinetic energy into the large-scale shear flow. Radially resolved measurements of the nonlinear kinetic energy transfer show that the flow is driven at the plasma boundary; temporally resolved flow measurements show a penetration of the resulting azimuthal flow into the central plasma region. The results provide an initial qualitatively test of theoretical predictions, and suggest how similar studies might be carried out in confinement devices.

## 1. Introduction

Due to the nearly two-dimensional nature of pressure-gradient driven drift turbulence in confined magnetic fusion plasmas, nonlinear kinetic energy transfer can result in the formation of large-scale ordered sheared $E \times B$ flows known as zonal flows. Experiments have demonstrated the existence of such flows (see [1] and references therein for a recent review) and the basic elements of the theory have also been recently reviewed [2, 3]. The zonal flows are driven by the nonlinear transfer of kinetic energy from the turbulent scales (typically occurring with normalized perpendicular wavenumber $k_\perp \rho_S < 1$ and diamagnetic frequency $\omega^*$) into the shear flow scale with $k_\theta \rho_S \sim 0$, $k_r \rho_S \sim 0.1$–$1$ and zero frequency). Here $\rho_S = C_S/\Omega_{Ci}$ where $C_S$ denotes the ion acoustic speed, $\Omega_{Ci}$ denotes the ion gyrofrequency and $(r, \theta)$ denote the minor radius and poloidal direction, respectively. The shearing action of the zonal flows then acts to regulate the turbulent correlation length and decorrelation time, and thus impacts the net transport rate arising from the turbulence. Recent tokamak experiments have also shown that confined plasmas can also have a net angular momentum in the absence of external momentum input; evidence exists that this rotation has its origin at the boundary of the plasma [4]. This rotation can impact plasma confinement as well as the MHD stability limits and thus is of significant interest for magnetic fusion. One recently published theoretical concept suggests that this so-called intrinsic rotation arises via the action of a turbulent non-diffusive stress acting in concert with a no-slip flow condition at the plasma boundary [5, 6].

In this paper we summarize recent work, carried out in a basic laboratory plasma device, that has been focused upon the basic physics of turbulent-shear flow interactions. Nonlinear turbulent-shear flow interactions are directly measured in a cylindrical helicon plasma device and found to lead to the development of an azimuthally symmetric radially sheared azimuthal flow by the action of the turbulent Reynolds stress which transfers kinetic energy into the large-scale shear flow. By making radially resolved measurements of the nonlinear kinetic energy transfer, we can show that the flow is driven at the plasma boundary; temporally resolved flow measurements show a penetration of the azimuthal flow into the central plasma region. The results provide an initial qualitatively test of theoretical predictions, and suggest how similar studies might be carried out in confinement devices.

## 2. Experiment

The work was carried out in the controlled shear decorrelation experiment (CSDX), which is a cylindrical helicon plasma device with a plasma radius of $\sim$5 cm and an axial length of $\sim$2.7 m. The plasma is immersed within a uniform solenoidal magnetic field that can be varied up to 0.1 T. Neutral argon gas is injected at the interface between the RF source operating at 13.56 MHz and the downstream vacuum chamber with wall radius $a = 10$ cm. Typical working gas pressures are in the range 0.2–0.4 Pa with flow rates of 10–20 sccm. The results discussed in this paper were obtained for power inputs of 1.5 kW and magnetic field of 0.1 T. A detailed discussion of the helicon source antenna and RF wave physics has been published [7], and a detailed discussion of the plasma equilibrium, onset of collisional drift waves and transition to a state of weak drift turbulence in the CSDX device has been published as well [8].

Equilibrium plasma density and temperature have been measured with RF compensated Langmuir probes [9]. The turbulent particle flux and Reynolds stress are measured with 4-tip probe arrays arranged to measure the spatial gradient of floating potential and ion saturation currents [8, 10–12]. The nonlinear turbulent kinetic energy transfer in the frequency domain is measured with a recently published technique that uses a $3 \times 3$ array of floating potential measurements [13]. Plasma flow has been measured using a multi-sided Mach probe arrangement as well as by time-delay estimation techniques [14]; the results show that fluctuation propagation speed is dominated by the plasma fluid $E \times B$ flow and thus provides a reasonable proxy for the azimuthal plasma $E \times B$ flow. A fast framing camera ($10^5$ frames s$^{-1}$) coupled to an $f/10$ 25 cm diameter telescope viewing parallel to the magnetic field through a window at the end of the device collected visible light from a distance of approximately 5 m away from the plasma source. The camera was focused on the probe axial position located approximately 1 m downstream from the plasma source exit plane. A detailed discussion of these optical measurements has been given elsewhere [15].

## 3. Results

The heat input from the RF source leads to a plasma density at $r = 0$ of nearly $10^{13}$ cm$^{-3}$ and a central electron temperature of about 3 eV (see figures 1(*a*) and (*b*)). Since the heat input

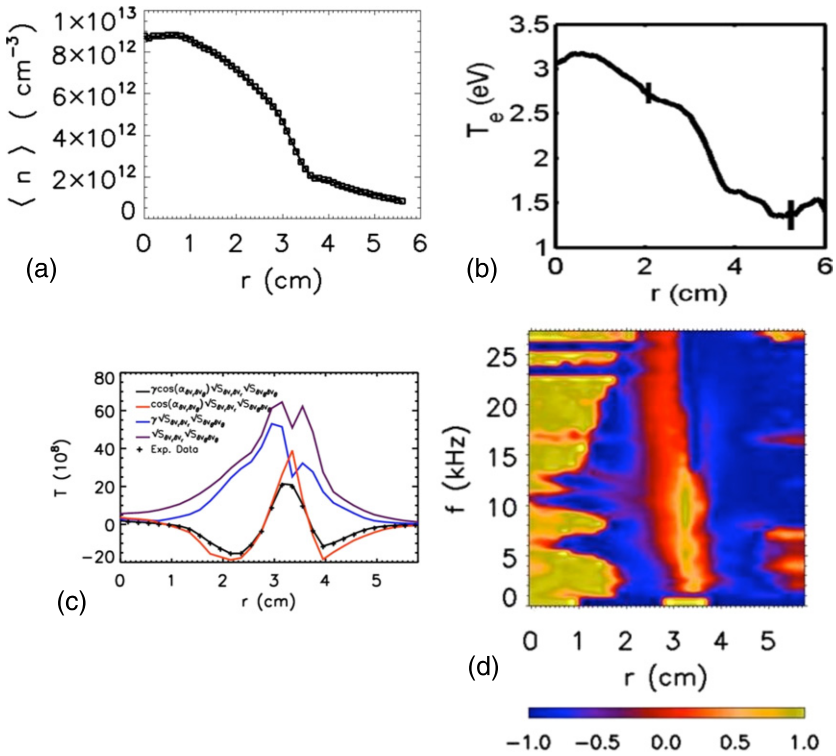

**Figure 1.** Radial distribution of time-averaged equilibrium (*a*) plasma density and (*b*) electron temperature. (*c*) Turbulent Reynolds stress $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ (black line), maximum possible Reynolds stress envelope $\sqrt{\langle \tilde{v}_r^2 \rangle \langle \tilde{v}_\theta^2 \rangle}$ (brown line), envelope modified by cross-coherency, $\gamma_{v_r v_\theta} \sqrt{\langle \tilde{v}_r^2 \rangle \langle \tilde{v}_\theta^2 \rangle}$ (blue line) and envelope modified by cross-phase, $\cos(\alpha_{v_r v_\theta}) \sqrt{\langle \tilde{v}_r^2 \rangle \langle \tilde{v}_\theta^2 \rangle}$ (red line). (*d*) Radial distribution of frequency-resolved cross-phase cosine, $\cos(\alpha_{v_r v_\theta})$.

vanishes for $r > a$, the plasma density and temperature in this region are much lower than in the central region. Thus a significant pressure gradient exists in the region from $r \sim 2$ cm out to $r \sim 4$ cm. It is this region where the collisional drift turbulence is concentrated; the earlier work shows that these fluctuations are dominated by $m = 1$ up to $m = 5$–6 drift fluctuations (here $m$ denotes the azimuthal mode number of the fluctuations). More recent work in this device demonstrated that the collisional drift turbulence leads to a finite turbulent Reynolds stress [10, 12] which can be decomposed into contributions from the turbulent fluctuation amplitude profile, and the cross-coherency and cross-phase between the fluctuating radial and azimuthal velocity components (figure 1(*c*)) [15, 16]. The cross-phase component plays the most significant role in determining the spatial structure of the total Reynolds stress. Since a negative divergence of the Reynolds stress (i.e. $\nabla_r \langle \tilde{v}_r \tilde{v}_\theta \rangle < 0$) is what leads to nonlinear drive of azimuthal flow, the results of figure 1(*c*) show that one should expect turbulent flow drive to occur over a narrow annular region located between $3.3 < r < 4.0$ cm. As shown in figure 1(*d*), the cross-phase exhibits a sharp change across this same radial location, showing that the cross-phase plays a key role in driving the sheared azimuthal flow.

Fast camera imaging allows the total visible light intensity to be measured with sufficient temporal resolution to permit direct observation of the weak drift turbulence. The average intensity is computed by averaging 1000 frames together and then subtracting the result from

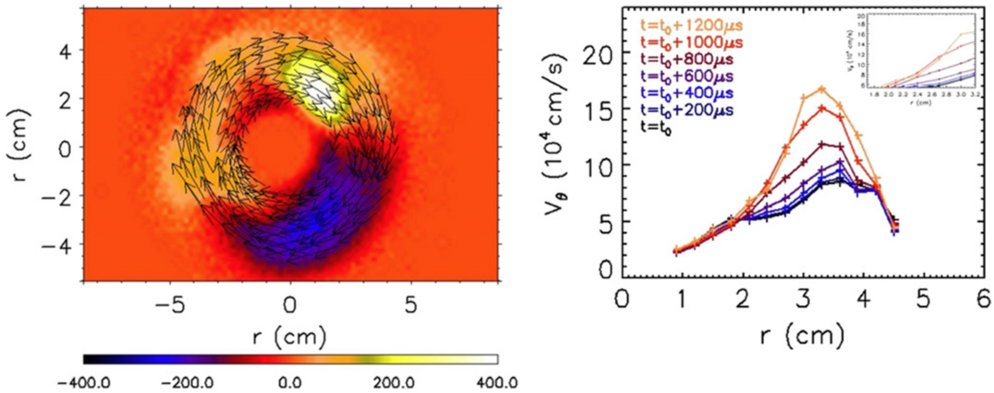


**Figure 2.** Left: single-frame ($1\,\mu$s exposure time) visible light intensity fluctuations showing finite $m$ light fluctuations associated with weak collisional drift turbulence. Velocity field computed from time-delay estimation technique using mutiple frames is superimposed, and shows the large-scale azimuthal flow associated with the combined plasma diamagnetic and $E \times B$ plasma fluid drift. Right: slow evolution of azimuthally averaged plasma flow, showing the growth of the radially sheared azimuthal flow.

the instantaneous intensity. The resulting intensity fluctuations track a combination of plasma electron density, temperature and neutral gas density. Figure 2 shows one typical snapshot of the visible light intensity fluctuations obtained in this manner. By tracking the motion of the intensity fluctuations using a time-delay estimation algorithm [17], the two-dimensional flowfield can be inferred with $\sim 50\,\mu$s resolution. One such flowfield showing the dominant radially sheared azimuthal flow is shown superimposed on the light intensity fluctuations in the left panel of figure 2. This flowfield can then be averaged over all azimuthal positions for a variety of times. The resulting time-resolved radial profile of azimuthal flow is shown in the right panel of figure 2. As discussed elsewhere [14], this flow is dominated by the plasma fluid $E \times B$ flow and thus provides a proxy for this quantity, which is the key component for zonal flow studies. These results also show that the radially sheared $m = 0$ flow exhibits a time variation on a $\sim$1 ms timescale, which is a few plasma azimuthal rotation times. The flow variation occurs over for $2.5 < r < 4$ cm; the peak variation seems to occur in the region near $r = 3$–$3.5$ cm.

Using a newly developed technique, we have also measured the nonlinear transfer of kinetic energy from the weak drift turbulence into the low frequency $m = 0$ shear flow. We first measure the dispersion relation, $k_\theta(f)$, using a two-point technique [18], and then identify the effective azimuthal mode number $m_{\mathrm{eff}} \equiv k_\theta r$ of the fluctuations (figure 3 upper left panel). We can then see that the frequency range $5 < f < 15$ kHz isolates fluctuations with $m_{\mathrm{eff}} > 1$ while the frequency range $f < 1$ kHz isolates fluctuations with average effective mode number $\langle m_{\mathrm{eff}}\rangle = 0$. Using this identification scheme, we can then directly measure the nonlinear transfer of kinetic energy from velocity fluctuations $\tilde{v}$ with $f_1 > 5$ kHz (corresponding to $m \geqslant 1$ fluctuations) into the large-scale ($m = 0$) velocity $V_\theta$ in the frequency range $f < 1$ kHz by measuring the cross bispectrum with a $3 \times 3$ probe array and then summing over the appropriate frequency ranges $T_{V_\theta} = \sum_{\substack{f\,<\,1\,\mathrm{kHz}\\ f_1\,>\,5\,\mathrm{kHz}}} \langle V^*(f)\tilde{v}(f-f_1)\cdot\nabla\tilde{v}(f_1)\rangle$. Here $\langle\cdots\rangle$ denotes an ensemble average over a sufficiently large ($\sim$1000) number of independent ensembles. Results obtained at $r = 3.8$ cm (upper right panel of figure 3) shows that the $m = 0$ fluctuations are driven by a nonlinear kinetic energy transfer from $m \sim 3$–$10$ fluctuations. The radial variation of this nonlinear flow drive can then be measured by moving the $3 \times 3$ array

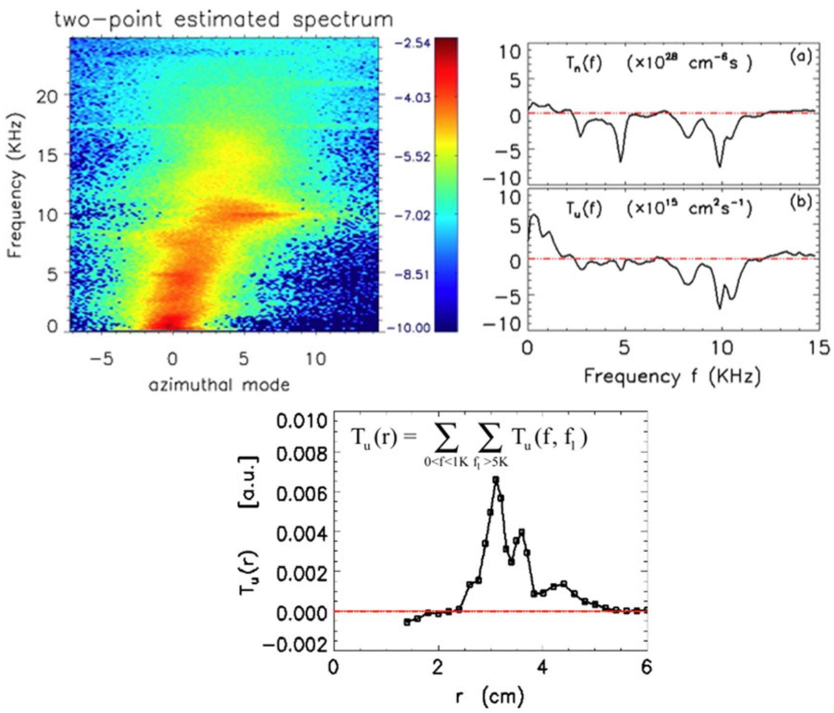


**Figure 3.** Upper left: dispersion relation, $k_\theta(f)$, of drift turbulence obtained using a two-point technique, allowing a mapping between frequency and azimuthal wave number. Upper right: frequency-resolved net nonlinear kinetic energy transfer into frequency $f$ from all other frequencies with $f > 5$ kHz, showing the net transfer of kinetic energy from frequencies $5 < f < 15$ kHZ (corresponding to $m = 1$ up to $m = 10$) into frequency $f < 1$ kHz (corresponding to $m = 0$). Data taken at $r = 3.8$ cm. Lower panel: radial profile of the net energy transfer into the $m = 0$ shear flow, showing that the nonlinear flow drive is localized to the region $3 < r < 4$ cm.

across the plasma. The result (lower panel of figure 3) indicates that $T_{V_\theta} > 0$ in the region between 2.8 and 4 cm consistent with a low-frequency shear flow driven by the higher frequency turbulent drift wave fluctuations; at other radii $T_{V_\theta} < 0$, consistent with a transfer of kinetic energy from the large-scale flow into the smaller scaled velocity fluctuations as expected for turbulent viscous momentum dissipation. Given the ∼0.6 cm radial and azimuthal extent of this array, the turbulent-driven shear flow region corresponds to a narrow (width ⩽1 cm) annulus centered around $r = 3.4$–3.5 cm.

## 4. Discussion and conclusions

Previous results have shown that the time-averaged Reynolds stress is self-consistent with the measured sheared azimuthal flow and estimated linear flow damping processes. The results presented here suggest that the shear flow is driven by the turbulence in an annular region localized to the outer region of the plasma pressure gradient; outside of the annulus the turbulence acts to damp the flow. The shear flow exhibits slow variations which are most pronounced in this annular region, and which are observed to couple to the plasma located at smaller radii. Presumably this momentum transport occurs via a combination of the usual type of turbulent momentum transport which gives rise to an effective turbulent viscosity, combined with ion–ion collisional viscosity. This picture is qualitatively similar to that proposed in recent theoretical work [6], and is also qualitatively similar to results from tokamak experiments [4]; similar studies of turbulent stress in toroidally confined plasmas may thus help determine the origins of plasma rotation in such experiments.

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