Sheared Flow and Fluctuation Dynamics Under Biasing in a Magnetized Laboratory Plasma

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I. Introduction

Experiments are described which study the nonlinear dynamics of weakly turbulent fluctuations and sheared flows during biasing of concentric ring electrodes in a linear magnetized plasma. It is found that drift fluctuations can be reduced and eventually fully suppressed (> 40 dB amplitude reduction) with positive ring biasing, $V_{bias} \sim 3T_e$. At high bias voltages, a second, higher frequency mode is observed. As reported previously [1], the fluctuations exhibit chaotic behavior with increasing dynamical complexity during this bias voltage increase. Linear local analysis indicates that at these higher biases, *azimuthal* flow shear-driven Kelvin-Helmholz (K-H) modes are stable, but *axial* shear-driven K-H modes are unstable. The rotation-driven interchange mode (IM) is also found to be unstable, and is more consistent with experimental data.

Ring biasing has little effect on "core" plasma rotation, which appears to be dominated by $E_r \times B_z$ rotation in the electron diamagnetic direction, where E_r is found to be in the -r direction, consistent with radial force balance. However edge electric fields and azimuthal flow profiles are more strongly modified by positive ring biasing, including the region around the radius of maximum linear growth rate for resistive drift waves (DW's). Axial flow is found to be "downstream" away from the source in the plasma center, but a return flow back toward the source at the plasma edge is observed without biasing. As positive bias is increased, this edge return flow is reduced in magnitude, and pushed radially outward. It is found that end vacuum pumping around a baffle plate strongly affects the chaotic dynamics and the ability to suppress the fluctuations under biasing. It is hypothesized that this pumping affects the edge flows - in particular the axial return flow – via neutral damping in the edge.

II. Experimental Arrangement

Experiments were conducted in the linear HelCat (Helicon-Cathode) device, a 4 m long, 0.5 m diameter device with axial magnetic field, $B_{z0} \leq 0.22$ T, and dual plasma sources [2]. Experiments described here utilized the RF helicon source alone, which consists of a helical half-twist, half-wavelength antenna with an inside diameter of 13 cm, operated at 10 MHz and 500 to 3500 W. Plasma pulses were ~ 250 ms long. $T_e \sim 5$ eV, across the plasma column, and the fill gas was argon. Typically, the ion sound speed, $c_s \sim 4\times10^3$ m/s, the ion sound gyroradius, $\rho_s = c_s/\omega_{ci} \sim 3$ cm, and ion-neutral collision frequency, $\nu_{in} \sim 2\times10^4$ s^{-1}.

A set of six concentric metal rings, spaced 7 mm apart and mounted on a square 15×15 cm ceramic substrate, were used to terminate the plasma column at z = 2.6 m from the helicon source [1,2]. Ring radii were ≈ 2.5, 3.0, 3.75, 4.5, 5.2, 5.9, 6.6 cm (plasma half maxium density radius ~ 6 cm, typically). Various biasing schemes have been utilized, however, this paper describes simple DC biasing where all six rings were connected together and biased with respect to the grounded vacuum chamber wall. Density and T_e profiles remained unchanged during biasing. As the magnetic field, B_0, is increased, drift fluctuations in HelCat transition to a broader spectrum with more fully developed turbulence, as has been reported elsewhere [3]. However, these experiments were conducted at low magnetic field (35 - 44 mTesla), so that dynamics closer to marginal stability could be observed. At higher B_0, similar effects to those discussed here were observed, but much higher bias voltage was typically required, which was sometimes found to affect the density profile (presumably due to the large electron currents being drawn by the rings).

III. Experimental Results

Figure 1 shows typical profiles of the electron density, measured by ion saturation current, I_{isat}, together with a 94 GHz interferometer, along with a half profile of the RMS I_{isat} fluctuation level. The fluctuations were dominantly m=1, propagated in the electron diamagnetic direction, and were identified as resistive drift modes [1]. The basic behavior of fluctuations as ring bias (with respect to the vacuum chamber wall) is increased from zero is shown in Fig. 2. As can be seen, low frequency fluctuations, identified as resistive DW's are reduced across the plasma radius for bias voltages up to ~ $3T_e$. At higher biases, a second, higher frequency instability (f ~ 10 kHz), which is more radially localized, is observed. Chaotic dynamics in the fluctuations are evident in cases of bias ≥ approximately $3T_e$ [1].

The flow behavior during biasing associated with this fluctuation data is shown in Fig. 3. As can be seen on the left, the azimuthal flow changes little at inner plasma

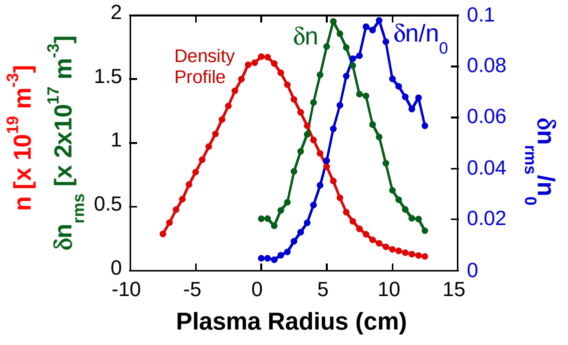


Fig. 1. Typcial HelCat helicon density profile, together with half profiles of rms density fluctuation level (δn), and normalized rms fluctuation level (δn/n), derived from I_{isat} on a double Langmuir probe assuming small δT_e, and a 94 GHz interferometer. Ring bias = 0V.

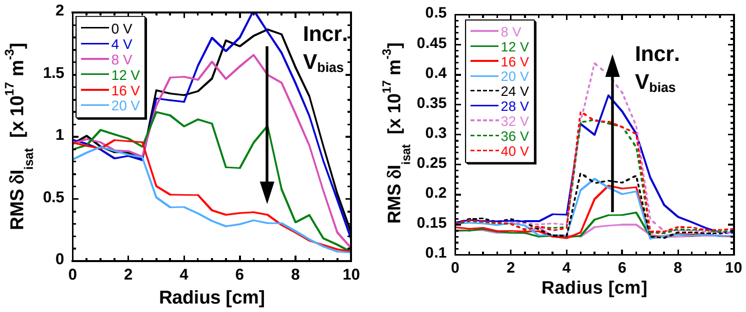
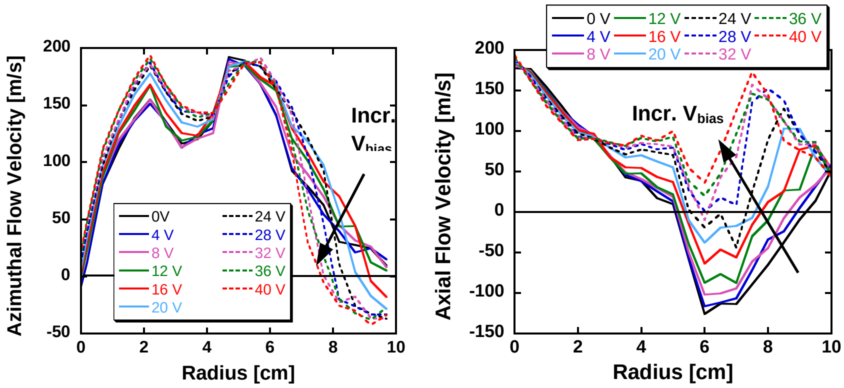


Fig. 2. Left: Low frequency and Right: high frequency ion saturation current fluctuation profiles vs. ring bias. Low freq.: low pass filtered, $f < 2$ kHz. Profiles for $V_{bias} > 20$ V similar to 20 V case. High freq.: band pass filtered, $5 < f < 15$ kHz. As ring bias is increased, low freq. fluctuations reduce, while high freq. fluctuations increase.

Fig. 3. Time-averaged plasma (ion) flow profile vs. V_{bias} measured by a Mach probe. Left: azimuthal flow (positve values are in the electron diamagnetic direction), Right: axial flow (positive values are in the direction away from the plasma source).



radii (R < 6 cm). In fact, it is found that rotation in this region is dominated by $E_r \times B_z$ flow in the electron diamagnetic direction, where E_r is in the –r direction. Such an inward pointing E_r appears to be consistent with ion radial force balance. Azimuthal flows and flow shear, however, are observed to change in the edge region, R > 6 cm, including at R ~ 8 cm, where the DW linear growth rate maximizes. In fact, at the highest biases, a reverse flow in the ion diamagnetic direction develops, as can be seen.

The axial flow shows even more interesting behavior, as can be seen on the right of Fig. 3. In the plasma center, R < 6 cm (approximately), downstream ion flow away from the source is observed. At outer radii, R > 6 cm, a return flow back toward the source is observed with zero bias. The return flow diminishes and eventually reverses with increased biasing.

Pumping at the vacuum chamber end is also found to affect the dynamics of the fluctuations under biasing. The experimental configuration is illustrated in Fig. 4. A second anode (for the cathode source), composed of a solid annulus and central grid which can be blocked with a shutter, is located 60 cm from the north end of the chamber (3.4 m from the helicon), and effectively forms a pumping baffle. There is a 2.5 cm radial gap at the wall. When the north pumping is removed or the 2.5 cm gap is filled with solid material, chaotic dynamics in the fluctuations with biasing are observed, and fluctuation suppression is easily achieved at low B-fields. However, when the gap is left open or filled with conducting mesh (so as to form a solid electrical contact, but allow gas flow), the chaos disappears, and fluctuation suppression is difficult or not possible. We hypothesize that the pumping modifies

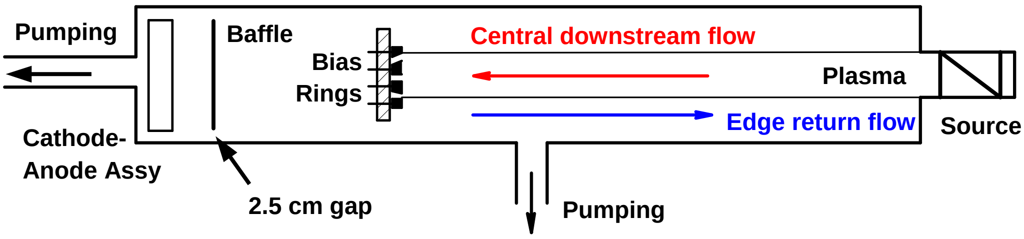


Fig. 4. Experiment schematic showing north end pumping (left) around baffle.

the edge plasma flows (since flows are more sensitive to neutral damping than the DW's).

IV. Linear Stability Analysis

Linear stability analysis has been undertaken investigating the roles of the resistive drift mode, axial and azimuthal shear flow-driven Kelvin-Helmholtz modes, and the rotationally-driven interchange mode [4]. Of course, this analysis will not describe the observed nonlinear dynamics, but it does give some indication of the modes in play. All models are radially local (i.e. WKB approximate in r) and utilize curve fits to measured profiles (n, T_e, flows, etc). DW and KH models are cylindrical, two-fluid, while the IM model is a single-fluid slab model. This analysis indicates that DW's are unstable with maximum linear growth rate (MLGR) at R ~ 8 cm, which is where the normalized DW amplitude is maximum in the experiment. The most unstable mode is m=1 as observed, and the model predicts the real frequency of this mode to within ~ 10%. Using flow profiles for high ring bias cases, azimuthal shear-driven KH is stable, while the axial shear-driven mode has MLGR at R ~ 6 cm and $\omega_{real}/2\pi$ ~ 10 kHz, as observed. However, it yields high values of the most unstable m and k_z, and a DW-like scaling, $\tilde{n}/n \approx \tilde{\phi}/T_e$ which are inconsistent with measurements. The IM also has MLGR at R ~ 6 cm and $\omega_{real}/2\pi$ ~ 10 kHz, but is most unstable m=3, k_z ~ $2\pi/(2.6)$ m^{-1}, and $5(\tilde{n}/n) \sim \tilde{\phi}/T_e$, much closer to experimental values. In biased cases where DW suppression is observed, this model *does not* show that the shearing rate exceeds the linear growth rate, $\omega_{ExB} > \gamma$, which might indicate that parallel flow shear plays a role in the suppression. However, it should be noted that this is a local model only. Solution of the radial eigenmode problems for these instabilities is currently underway.

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References

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