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Chaos, Intermittency, and Sheared Flow Dynamics Under Biasing and Boundary Condition Changes in a Magnetized Laboratory Plasma

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I. Introduction and Experimental Arrangement

This paper reports on a set of DC biasing experiments in a large-scale linear magnetized plasma which investigate the nonlinear dynamics of weakly turbulent drift wave (DW) and Kelvin-Helmholtz (KH) fluctuations in the presence of sheared azimuthal and parallel flows. Biasing was accomplished via a set of six concentric copper rings that terminate the plasma column. It was found that as the positive DC bias is increased from zero to $V_{bias} \sim 10T_e$, plasma flow shear increased by a modest amount, but penetrated into the plasma core from the edge. Concurrently, drift fluctuations were suppressed, then the KH instability was excited. With increasing bias, fluctuations went through period doubling bifurcations, eventually becoming chaotic, with the correlation dimension increasing from ~ 1 to ~ 3.

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 [1]. 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. Ring radii were ≈ 2.5, 3.0, 3.75, 4.5, 5.2, 5.9, 6.6 cm. Various biasing schemes have been utilized (DC, AC, between various rings, etc.), 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 broader spectrum, more fully developed turbulence, as has been reported elsewhere [2]. However, these experiments were conducted at low magnetic field (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).

II. Experimental Results

A typical electron density profile, 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, is shown in Fig. 1. The fluctuations were dominantly m=1, propagated in the electron diamagnetic direction, and were identified as resistive drift modes since they 1) peak in the middle of the density gradient, 2) have $\omega \approx \omega^* - \omega_\theta$, where ω^* is the electron diamagnetic frequency, $\omega_\theta = v_\theta(m/r)$, v_θ is the azimuthal flow velocity, and 3) have $\tilde{n}/n \approx \tilde{\phi}/(k_B T_e/e)$. Additionally, linear analysis for these parameters shows m=1 drift waves to be unstable.

Figure 2 shows a typical example of the plasma potential profile, measured by a floating probe and corrected for T_e, as the ring bias, $V_{bias,}$ was increased. Fig. 3 shows azimuthal and axial flow profiles measured by a Mach probe, as V_{bias} increased. It can be seen that as the bias increased, the flow and its radial gradient (shear) move inward from the plasma edge. There is also a change in magnitude of edge axial flow.

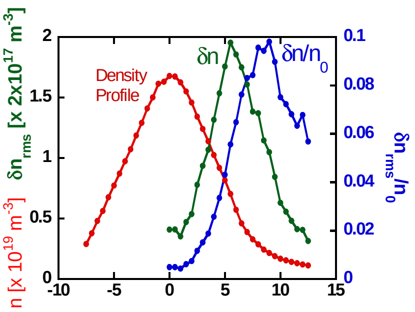

Fig. 1. Typcial HelCat helicon density profile, together with half profiles of rms density fluctuation level (δn), and normalized rms fluctuation level ($\delta n/n$), derived from I_{isat} on a double Langmuir probe assuming small δT_e, and a 94 GHz interferometer. Ring bias = 0V.

Fig. 4 shows profiles of the RMS I_{isat} fluctuation level in two frequency bands as V_{bias} is increased. At values of V_{bias} less than ~ 12 - 16 V, the fluctuations were dominated by the m=1 drift mode at f ~ 1 kHz (*cf.* Fig. 4(a)). As V_{bias} was increased, the amplitude of these fluctuations reduced, eventually being fully suppressed by more than 40 dB. At V_{bias} > 10 V roughly, a new higher frequency mode appeared at f ~ 10 kHz. This mode was more spatially localized, and had higher relative potential fluctuations, $\tilde{\phi}/(k_B T_e/e) \sim 5(\tilde{n}/n)$, than expected for drift modes. We tentatively identify this as a KH instability. Though linear analysis including *either* axial flow shear [3] , *or* azimuthal flow shear [4] shows K-H modes to be below the instability threshold, the presence of the observed levels of shear in both directions likely

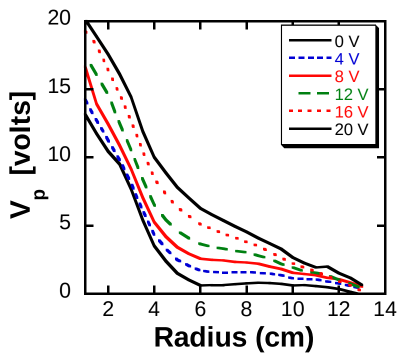

Fig. 2. Plasma potential profile vs. radius for various ring bias values, measured by a floating probe and corrected for T_e.

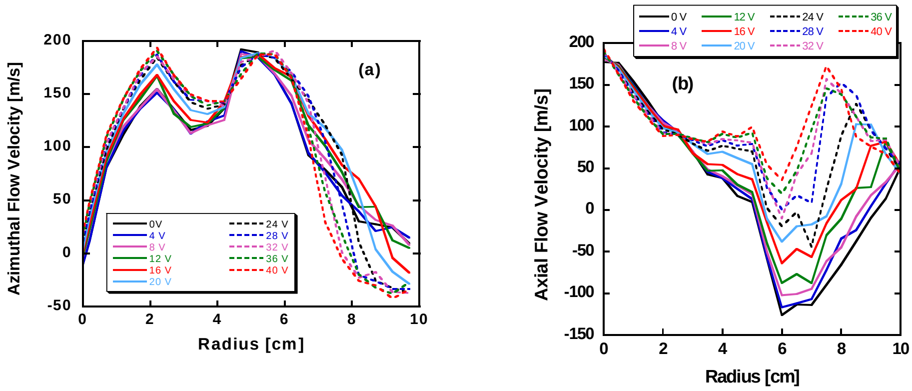

Fig. 3. Time-averaged plasma flow profile vs. V_{bias} measured by a Mach probe. a) azimuthal flow, b) axial flow.

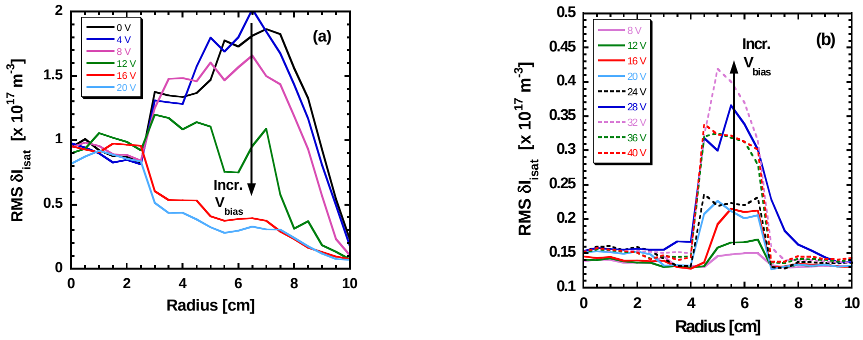

Fig. 4. (a) Low frequency and (b) high frequency ion saturation current fluctuation profiles vs. ring bias. Low freq.: low pass filtered, f < 2 kHz. Profiles for V_{bias} > 20 V similar to 20 V case. High freq.: band pass filtered, 5 < f < 15 kHz. As ring bias is increased, low freq. fluctuations reduce, while high freq. fluctuations increase.

destabilizes this mode, and a detailed stability calculation is now underway.

The spectral/dynamical nature of the fluctuations was also observed to change as V_{bias} was increased. Fig. 5 plots I_{isat} vs. time and the corresponding phase lag plots, calculated by a standard delay embedding technique [5], for three values of V_{bias}. At V_{bias} = 0 V, the signal was quasi-periodic, and the spectrum shows one dominant peak (at f ≈ 800 Hz in this case). At V_{bias} = 15 V, a period-doubling bifurcation has occurred, and the phase plot exhibits a double loop structure. The frequency spectrum shows corresponding peaks at half-frequencies of 800 Hz and its harmonics. At V_{bias} = 25 V, the dynamical complexity has increased, the phase plot is more random-like, and the corresponding spectrum is more broadband. Still higher bias leads to a truly random-like phase plot, which exhibits intermittent bursts of fluctuations, as shown in Fig. 6. Figure 7 illustrates this change in dynamical complexity by plotting the correlation dimension, D, calculated from phase-delay self-similar regions, vs. V_{bias}. It can be seen that D > 2 (which is one measure of the existence of deterministic chaos [6]) occurs at V_{bias} ~ 20 V.

III. Discussion

The qualitative dynamical behaviour of drift and K-H fluctuations under DC biasing described above holds generally under a variety of conditions in HelCat (fill pressure, B-field,

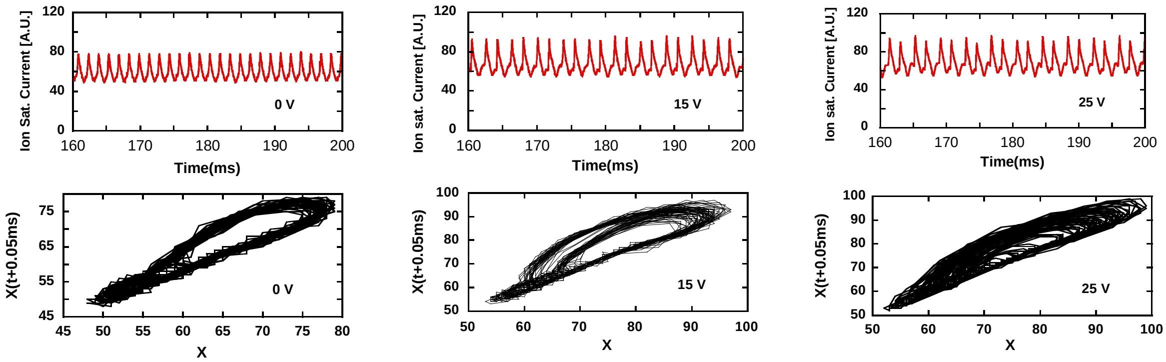

Fig. 5. Ion saturation current vs. time (upper) and corresponding phase lag plots at ring biases of 0 V, 15 V, and 25 V. Probe at R = 6 cm.

RF power, etc). That is, the dynamical complexity generally increases with bias, flow profiles change, DW's are suppressed, and KH modes are excited. However, the details of the dynamics have been found to depend very sensitively to edge boundary conditions (i.e. location and grounding of edge and chamber end conductors), and B_0. While the dynamical complexity generally increases with magnetic field, B_0, changes as little as 0.5 mTesla (with other parameters fixed) can produce marked effects in the signal. Such behaviour is typical of chaotic systems with the change of a critical tuning parameter. The tuning parameter in this case may be the E×B rotation frequency, $\omega_{E\times B} = v_{E\times B}(m/r)$ profile. Light *et al.* have shown, in a linear theory of coupled drift-KH modes in the presence of E×B flow shear, that there is a singularity in the radial wavenumber, k_r, when $\omega = \omega_{E\times B}$, where ω is the fluctuation frequency and $\omega_{E\times B}$ is the local E×B frequency [7]. Thus, small changes in the $\omega_{E\times B}$ profile could produce large effects in the fluctuations. Work is underway to extend this theory to include parallel flow, and to model the experiment with a fully nonlinear fluid code.

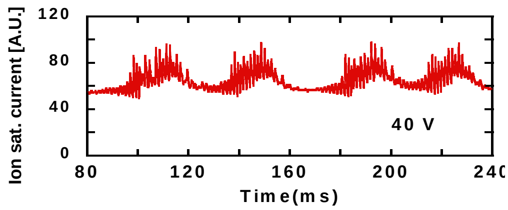

Fig. 6. Ion saturation current vs. time at 40 V bias. Probe at R = 6 cm.

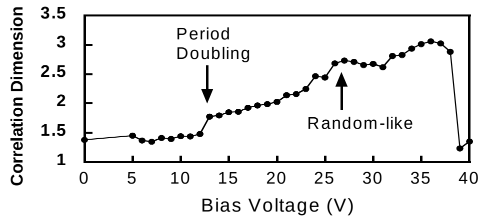

Fig. 7. Correlation dimension, D, of ion sat. fluctuations vs. rings bias. Probe at R = 6 cm.

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