Final Report

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Project Title: *Investigation of Intermittent Turbulence and Turbulent Structures in the Presence of Controlled Sheared Flows*

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I. Overview

The focus of this work has been to investigate the generation of intermittent convective structures, variously known as “blobs” or “avaloids”, which are widely observed in both laboratory and fusion devices. Although a significant amount of research into the polarization charging and convection of blobs, as well as scalings with magnetic field and plasma density, has previously been conducted, less work has addressed the generation mechanism of these structures. In particular, a detailed study was undertaken of the interaction of sheared flows with turbulent instabilities in the plasma edge, as a likely source of these convective blobs.

Experiments were conducted in i) the Large Plasma Device (LAPD) at the Basic Plasma Science User Facility at UCLA [1], ii) the HelCat device at U. New Mexico [2] using HelCat’s RF helicon source, and iii) using HelCat’s thermionic cathode source (a smaller diameter version of the cathode source in the LAPD). The turbulent edge fluctuations and velocity (flow) shear profiles present in these three cases are significantly different. Fluctuations in the LAPD, a much larger plasma than HelCat (LAPD: 60 cm plasma diameter), always show the characteristics of fully developed turbulence (i.e. broad spectrum). There is a natural edge azimuthal velocity shear layer that is localized to a few cm radially, which is on the same scale as the radial correlation length, $L_{c,r}$, of the turbulence. Fluctuations in HelCat, on the other hand, which has a significantly smaller plasma (15 cm diameter plasma), vary from coherent to weakly turbulent with the helicon source, with azimuthal velocity shear scale length, L_{shear} that is significantly less than the large correlation lengths of the fluctuations, $L_{c,r} \sim L_{c,\theta} \sim \text{several cm} > L_{\text{shear}}$. HelCat cathode plasmas (~ 15 cm diameter) are always weakly turbulent, with shorter turbulent correlation lengths on the same scale as the edge velocity shear layer, $L_{c,r} \sim L_{\text{shear}}$, similar to that in the LAPD. Together these three cases span a fairly broad range of turbulence and velocity shear parameter space.

The basic findings of our work are as follows. In helicon plasmas (HelCat) with weakly turbulent fluctuations with scale lengths greater than velocity shear scale lengths, L_{shear} , no blobs have been observed. Increasing flow shear, affected by end electrode biasing to modify plasma $E_r \times B_z$ profiles, is found generally to increase the dynamical complexity of the (weak) turbulence, including producing chaotic fluctuations. In the more turbulent cathode plasmas (cases i and iii), blobs were observed consistently, and their creation and detachment was clearly associated with the edge flow shear layer in each case. However, our experiments showed limited effect by biasing on the velocity shear, and on the blob dynamics.

II. Weakly Turbulent, Long Correlation Length Case – Chaotic Dynamics

Figures 1 and 2 show the HelCat device at UNM, and the end ring electrode biasing arrangement respectively. By changing voltage on one or more of the rings with respect to (w.r.t.) the grounded chamber wall, the $E_r \times B_z$ flow profiles can be affected. Figure 3 shows typical power spectra of ion saturation current profiles measured by Langmuir probes at $R = 8$ cm radius for a) cathode plasmas, which have broadband spectra, and 2) helicon plasmas, which are weakly turbulent.

When biasing of ring electrodes was performed in the case of cathode plasmas, some changes were seen in the fluctuation spectra and azimuthal velocity profiles, but no significant differences were observed in either the blob dynamics or the turbulence dynamics. In contrast, depending on parameters, large changes were observed in the flow profiles and fluctuation dynamics under ring biasing of helicon plasmas. For example, Fig. 4 shows an example of ion

Fig. 1. Left: HelCat (HELicon-CATHode) plasma device at UNM shown from helicon source end. Right: Typical helicon source density profile, $n_0(R)$, and half profiles of density fluctuations, δn , and normalized density fluctuations, $\delta n/n_0$.

Fig. 2. Upper: Ring biasing arrangement shown for the case of helicon plasmas. For cathode plasmas, the thermionic cathode was used as the source. Lower left: Concentric bias end ring electrodes. Rings are copper, mounted on a ceramic substrate. Kepco power op amps are used to drive the rings (± 20 V, ± 20 A, 20 A/100 μ s slew rate).

Fig. 3. Typical power spectra of ion saturation current, I_{isat} , at $R = 8$ cm for HelCat cathode plasma (left) and helicon plasma (right) with no electrode biasing. Argon, $B_0 = 350$ G, $P_{RF} = 1400$ W.

Fig. 4. Top: Ion saturation current fluctuations vs. time for 10 V bias ($\sim 2 \times T_e$) (left) and 40 V bias ($\sim 8 \times T_e$) (right) in HELCAT helicon plasma. Bottom: phase lag plots of the fluctuations for the same cases calculated by delay embedding [5]. At 10 V, fluctuations have undergone a chaotic period doubling bifurcation. At 40 V, fluctuations are intermittent, and chaos dimension has increased. Argon, $B_0 = 350$ G, $P_{RF} = 1400$ W, fill pressure = 2.3 mTorr.

saturation current during an entire 240 ms discharge, together with the corresponding phase space plots of the fluctuations during steady state. Density fluctuations can be seen as the “fuzz” in the trace. At moderate ring bias voltage, a double looped phase space structure can be seen, which has been shown to correspond to a chaotic period doubling bifurcation [3]. At the higher 40V bias, the fluctuations have become intermittent, and the correlation dimension – a measure of dynamical complexity [4,6] – has increased. A plot of correlation dimension versus ring electrode bias is shown in Fig. 5, together with phase plots corresponding to the approximate bias where the fluctuations transition to chaos.

Changes in both axial and azimuthal flow profiles, including shear, were observed during ring biasing and the changes in fluctuation dynamics. It is believed that increasing flow shear is directly responsible for changes in the fluctuations, probably due to modifications in the linear stability of the underlying drift instabilities. Follow-on work will investigate this hypothesis in detail using a numerical stability solver. Figure 6 shows an example of axial and azimuthal flow profiles measured by a Mach probe vs. ring bias. It can be seen that there are clear changes in the velocity shear in both directions. We note, however, that the shear flow changes occur on a scale of ~ 2 cm, which is significantly less than the radial or azimuthal correlation length of the fluctuations ($L_{c,r}$, $L_{c,\theta}$ respectively), which are $\sim$ several cm.

In addition to the fundamental observation discussed above that the dynamical complexity of density fluctuations increases with ring electrode bias, the nature of the fluctuation dynamics in helicon plasmas with a number of plasma parameters has been studied and documented during the course of this work. Observations include the following.

1. The dynamical complexity the fluctuations generally increases with RF source power.

2. The dynamical complexity the fluctuations generally increases with gas fill pressure. This is believed to be due to increasing collisionality (with neutrals), which increases plasma resistivity, and is destabilizing to the drift instability.
3. The dynamical complexity of the fluctuations generally increases background magnetic field, B_0 . However, these changes are not monotonic. At a number of magnetic fields, sudden transitions in the dynamical complexity (coherent vs. chaotic, for example) are

Fig. 5. Upper left: Correlation dimension of ion saturation current at $R = 7$ cm versus ring electrode bias voltage for HelCat helicon plasma, showing increasing dynamical complexity with bias. Three different embedding delays, τ , are shown, which are all consistent. Transition to chaos at $D = 2$ – around 18 V. Right: corresponding phase plots at the approximate transition to chaos in 2D (upper) and 3D (lower). Details of the calculations and interpretation are given in ref [3]. Argon, $B_0 = 350$ G, $P_{RF} = 1400$ W

Fig. 6. Plasma flow versus radius for various biases, measured by a four tip Mach probe in HELCAT. Left: axial flow, right: azimuthal flow. All rings connected together, and bias w.r.t. vacuum chamber wall. Positive denotes the electron diamagnetic direction. Central sound speed, $c_s \approx 3 \times 10^5$ m/s.

observed with changes of as little as 4 G (1% change or less in B_0). This behavior is suggestive of the existence of a nonlinear dynamical *tuning parameter* [4,5].

4. A single mesh electrode (grid) placed in front of the helicon source (*cf.* Fig. 2) can qualitatively produce the same changes in flow profiles and fluctuation dynamics as the end ring electrodes. Both with the grid and rings, changes in radial electric field and velocity profiles occur primarily at the plasma edge.

III. Fully Developed Turbulence, Short Correlation Length Case – Blob Dynamics in a Sheared Flow

The dynamics of the interaction between sheared flows and fluctuations were markedly different in the more turbulent cathode plasmas – both in HelCat and LAPD. Turbulent correlation lengths in cathode plasmas have been found to be much shorter than in helicon plasmas, typically around $L_{c,r} \sim 1 - 3$ cm depending on parameters such as magnetic field and gas fill pressure. At the edge of the cathode, a strong velocity shear layer has been observed in all cases – both in the axial and azimuthal directions. A typical example from LAPD is shown in Fig. 7, where it can be seen that there are steep velocity gradients with scale lengths, L_{shear} , of a few cm. That is, the scale length of the shear layer is of the order of, or larger, than the radial turbulent correlation length: $L_{\text{shear}} \sim L_{c,r}$. This is further illustrated in Fig. 8, where a 2D “correlation image” of ion saturation current fluctuations is shown. In this figure, a shear layer in the azimuthal velocity (v_y) is present between $\sim 28 - 32$ cm. The velocity shear gives rise to the skewed turbulent eddy shape that can be seen in the figure, due to eddy-stretching [7].

It is clear that the existence of a velocity shear layer of scale length of the same order as the turbulent radial correlation length is associated with the creation of intermittent turbulent structures, which can become detached and form blobs. The detailed physics of this process, and the degree to which it can be affected by external control of mean $E_r \times B_z$ flow shear are not yet clear. We note that it has been reported elsewhere [8], that very strong biasing in LAPD plasmas, for example, $V_{\text{bias}} > 300$ V ($\sim 40 \times T_e$), has achieved suppression of cross-field turbulent

Fig. 7. Axial (v_z) and azimuthal (v_y) velocity profiles in a typical LAPD plasma, as measured by a Mach probe. Cathode edge is at 35 cm. Helium, $B_0 = 1$ kG, discharge current = 2.5 kA.

Fig. 8. 2D correlation image of ion saturation current in an LAPD plasma. Here, two axially-separated probes measuring I_{isat} are cross-correlated over many shots to form an image. The first probe is located at $x = 30.0$ cm, $y = 2.0$ cm. The second probe is scanned over the entire plane shown. An image of a turbulent eddy structure results. Here, there is an azimuthal (v_y) velocity shear layer between $x \sim 28 - 30$ cm, which skews the eddy as shown. Helium, $B_0 = 1$ kG, discharge current = 2.5 kA.

transport, reminiscent of the observed suppression of fluctuations in HelCat helicon plasmas when relatively strong shear layers are present, with $L_{\text{shear}} < L_{\text{c,r}}$.

IV. Graduate and Undergraduate Student Researchers Supported

In addition to Profs. Carter and Gilmore, both plasma physics Jr. Faculty, one full time UNM graduate student, Mr. Lincan Yan, has been supported on this grant, as well as two undergraduates (Mr. Anton Stepanov – UCLA, and Mr. Jake Hollowell – UNM). Mr. Yan conducted his Ph.D. dissertation research in this area of blob generation, and has been the main experimenter on HELCAT. He is currently writing his dissertation. Mr. Jake Hollowell has assisted in the construction of experimental apparatus and diagnostics, as well as in conducting experiments.

One undergraduate student, Mr. Anton Stepanov, was involved in the effort at UCLA over the last year. Anton assisted with the design and construction of the five-tip flux probe and also with the design and fabrication of diagnostic electronics associated with the probe. In performing the electronics development, Anton learned about techniques for achieving high common-mode rejection ratios in differential amplifiers and helped significantly improve our standard in-house design for instrumentation amplifiers.

V. Publications and Presentations

The following journal publication and conference presentations related to this project have been made.

1. A. G. Lynn, M. Gilmore, C. Watts, J. Harerra, R. Kelly, S. Xie, L. Yan and Y. Zhang (2009). *Rev Sci Instrumen.* **80**, 103501.
2. *Chaos, Intermittency, and Sheared Flow Dynamics Under Biasing and Boundary Condition Changes in a Magnetized Laboratory Plasma.* M. Gilmore, T.R. Hayes, S.

Xie, L. Yan, and C. Watts. Contributed oral presentation at the 36th European Physical Society Division of Plasma Physics, Sophia, Bulgaria, June 29 – July 3, 2009.

3. *Observation of Chaos in a Magnetized Laboratory Plasma Due to an Applied Electric Field.* S. Xie, C. Watts, M. Gilmore, L. Yan. Poster presentation at the 50th Annual Meeting of the American Physical Society Division of Plasma Physics, Nov. 17 - 21, 2008, Dallas, TX, USA.
4. *Convective Blobs in the Presence of Sheared Flows in a Magnetized Laboratory Plasma.* L. Yan, M. Gilmore, C. Watts. Poster presentation at the 50th Annual Meeting of the American Physical Society Division of Plasma Physics, Nov. 17 - 21, 2008, Dallas, TX, USA.
5. *Nonlinear Dynamics of Fluctuations in the Presence of Sheared Parallel and Perpendicular Flows in a Magnetized Laboratory Plasma.* M. Gilmore, L. Yan, S. Xie, C. Watts, and A.G. Lynn. Presentation at the 2008 IEEE International Conference on Plasma Science (ICOPS), June 15 - 19, 2008, Karlsruhe, Germany.
6. *Nonlinear Dynamics of Fluctuations in the Presence of Sheared Flows in a Magnetized Laboratory Plasma.* M. Gilmore, L. Yan, S. Xie, and C. Watts. Presentation at the 2008 US Transport Task Force Meeting, March 25 – 28, 2008, Boulder, CO, USA.
7. *Observation of Chaos in a Magnetized Laboratory Plasma under the Influence of Variable Biasing.* S. Xie, C. Watts, M. Gilmore, and L. Yan. Poster presentation at the 49th Annual Meeting of the American Physical Society Division of Plasma Physics, Nov. 12 - 16, 2007, Orlando, FL, USA.
8. *Nonlinear Dynamics of Fluctuations and Convective Blobs in the Presence of Sheared Flows in a Magnetized Laboratory Plasma.* L. Yan, M. Gilmore, S. Xie, and C. Watts. Poster presentation at the 49th Annual Meeting of the American Physical Society Division of Plasma Physics, Nov. 12 - 16, 2007, Orlando, FL, USA.
9. L. Yan, M. Gilmore, S.W. Xie, and C. Watts, “Nonlinear Dynamics of Turbulent Fluctuations in a Linear Magnetized Plasma with Controlled Flow Shear.” Talk to be presented June 18, 2007 at the IEEE International Conference on Plasma Science, June 18 – 22, 2007, Albuquerque, NM.
10. L. Yan, M. Gilmore, N. Crocker, T.A. Carter and W.A. Peebles, “Investigation of Intermittent Transport and Turbulent Structures in the Presence of Controlled Sheared Flows.” Poster presented at the 48th annual meeting of the APS DPP, Oct. 30 – Nov. 3, 2006, Philadelphia, PA.
11. S.W. Xie, M. Gilmore, C. Watts, L. Yan, A. Lynn, C.T. Abdallah, and A.S. Ware, “Investigation of Active Feedback Control of Turbulent Transport in a Magnetized Laboratory Plasma.” Poster presented at the 48th annual meeting of the APS DPP, Oct. 30 – Nov. 3, 2006, Philadelphia, PA.

In preparation:

1. S. Xie, M. Gilmore, C. Watts, and L. Yan. “Observation of Chaos in Magnetized Laboratory Plasma under the Influence of Variable Biasing”. To be submitted to *Chaos*.

VI. Patents and Copyrights

No patents or copyrights have resulted from this work.

VII. Summary

In summary, the main conclusions of this work areas follows.

1. In weakly turbulent helicon plasmas with relatively radial long correlation lengths, electrode biasing to modify edge velocity shear layers whose scale length, $L_{\text{shear}} <$ the radial correlation length of the fluctuations, is found to produce rich changes in the dynamics of the fluctuations, including inducing chaotic behavior. The details of this process depend on a number of global plasma parameters, such as magnetic field, RF source power, and gas fill pressure (neutral collisionality).
2. The creation of intermittent, detached turbulent “blob” structures is clearly associated with the existence of a velocity shear layer whose scale length is of the order of the with radial correlation lengths of broadband turbulence. The detailed physics of this process are not yet clear. Blobs are routinely observed in more turbulent cathode plasmas, but have not yet been observed in weakly turbulent helicon plasmas.
3. Moderate electrode biasing, $V_{\text{bias}} < 40 \times T_e$, has shown no effects so far on turbulence or blob dynamics.

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