

Observations of low frequency oscillations due to transverse sheared flows

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This Letter details observations of low frequency (i.e., $\omega \leq \Omega_i$, where Ω_i is the ion cyclotron frequency), coherent instabilities in the Auburn Linear Experiment for Instability Studies (ALEXIS). In the ALEXIS device, which is a 1.8-m long magnetized plasma column, the observed instabilities are excited by the presence of sheared flows in the plasma that are transverse to the axial magnetic field. The instabilities have long azimuthal wavelengths ($m \leq 2$) and are localized in the plasma to regions where the sheared flow is maximized and are anticorrelated to both density gradients and field aligned currents. © 2003 American Institute of Physics.
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The role of transverse flow shear in magnetized plasmas is a topic of much relevance to the plasma physics community. Here, flows are driven by the presence of an electric field (\mathbf{E}) that is transverse to a magnetic field (\mathbf{B}), thereby giving rise to sheared flows in the direction of $\mathbf{E} \times \mathbf{B}$. Within the fusion community, a great deal of excitement has been generated from studies of velocity shear stabilization of low frequency modes in toroidal devices. Experiments in a number of toroidal devices have demonstrated that control of these sheared flows is an important mechanism for achieving high performance conditions in fusion plasmas.^{1,2} While these studies show promise, the exact mechanisms that lead to stabilization and the resulting accessibility of enhanced confinement regimes (i.e., so-called H modes) are still being debated.^{3–5}

Consequently, the primary objective of this experiment is to isolate and control the velocity shear in a simple linear experiment and to characterize the response of the plasma to sheared flows. In these experiments, velocity shear is found to have a destabilizing effect on the plasma. This clearly contrasts with many of the observations of enhanced confinement regimes in toroidal devices. Nonetheless, there is evidence in both tokamak⁶ and stellarator⁷ devices that $\mathbf{E} \times \mathbf{B}$ driven flows can be destabilizing. This raises the question of whether shear flow is a cause or effect of H modes.

In space plasmas, $\mathbf{E} \times \mathbf{B}$ driven flows are often associated with satellite and sounding rocket observations of ion outflows from the ionosphere^{8,9} as well as low frequency waves.^{10–12} Several mechanisms have been considered for these phenomena, including magnetic field aligned currents^{13,14} and Kelvin–Helmholtz instabilities,^{15,16} but no single mechanism appears to be completely adequate in explaining the observed phenomena. However, theoretical work at the Naval Research Laboratory (NRL) has shown that sheared $\mathbf{E} \times \mathbf{B}$ driven flows are an important and often critical component of the aforementioned phenomena.^{17–20}

Q-machines,^{21,22} linear plasma columns,^{23,24} low temperature toroidal devices,²⁵ and large-volume experiments²⁶ are used to explore the roles of velocity shear in both transverse and parallel flows on particle and wave transport in magnetized plasmas. While these experiments cannot access the types of plasma parameters in either fusion or space plasmas, important scalings are preserved. These experiments can provide valuable new insights into key plasma processes that would be otherwise difficult to explore in devices with complex geometry such as tokamaks.

The goal of experiments at Auburn University is to develop a more complete understanding of the role of both stabilizing and destabilizing effects of $\mathbf{E} \times \mathbf{B}$ driven flows. Experiments described in this letter are performed using a simple experimental geometry—a cylindrical plasma column—to facilitate exploration of the basic physics without the difficulties associated with more complex experimental configurations.

This Letter summarizes the initial results of an experimental investigation of low frequency instabilities, at or below the ion cyclotron frequency, which arise due to the presence of sheared $\mathbf{E} \times \mathbf{B}$ flows in the plasma. Descriptions will be given of the experimental hardware and diagnostics used for this investigation. This will be followed by a discussion of the experimental measurements. Finally, a discussion of the physical mechanisms that may be responsible for the observed instability will be presented.

Experiments are performed in the ALEXIS device—the Auburn Linear Experiment for Instability Studies. ALEXIS is 180 cm long, 10 cm diameter stainless steel vacuum vessel. The chamber consists of a water-cooled section, followed by a six-way cross section, a 100 cm long section that has numerous QF 40 (“quick flange” style –40 mm diameter) diagnostic ports, and a final six-way cross section.

Experiments in ALEXIS are generally performed using helium gas. Plasmas are generated using an array of three, 0.25 mm diameter tungsten filaments that are heated with

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TABLE I. Operating conditions in ALEXIS.

Peak magnetic field (B_{\max})	1000 Gauss
Typical magnetic field (B_{typ})	70–100 Gauss
Plasma density (n_e)	$8 \times 10^{15} \text{ m}^{-3}$
Electron temperature (T_e)	5–10 eV
Ion temperature (T_i)	<0.05 eV
Operating pressure (helium)	<0.8 mTorr
Ion cyclotron frequency (f_{ci})	~25 to 40 kHz
Mean free path	9 cm
Ion gyroradius/Chamber radius (ρ_i/a)	0.1–0.2

currents up to 7 A into thermionic emission. The plasma is generated by allowing the filaments to emit electrons in a current-limited mode ranging from 100 to 300 mA. The plasma then passes through a grounded electrode and drifts into the main experimental volume. The plasma potential remains within 5 V of the laboratory electrical ground. This configuration allows ALEXIS to operate under reproducible plasma conditions. Plasma parameters are measured using single²⁷ and triple²⁸ Langmuir probes. Typical operating conditions and plasma parameters for ALEXIS are listed in Table I.

The key element of this experiment is a series of four concentric rings at the end of ALEXIS. These rings are mounted on a Macor block and oriented perpendicularly to the axial magnetic field. Each ring can be independently biased to establish a desired radial potential structure in the plasma. In the experiments described in this Letter, Rings 1, 2, and 4 are held at fixed bias voltages while the bias voltage on Ring 3 is varied. Rings 1 and 2 are set at the same bias voltage, $V_1 = V_2 = -120 \text{ V}$. Ring 4 is grounded at $V_4 = 0 \text{ V}$.

In these experiments, a low frequency instability is observed to grow in the plasma as the bias voltage on Ring 3 is varied. At a positive bias voltage, there is a significant magnetic field aligned current of up to 100 mA due to electron collection. At negative bias voltages, field aligned currents are $|I_3| \leq 5 \text{ mA}$. A fast Fourier transform (FFT) spectrum of the floating potential on a Langmuir probe is shown in Fig. 1. The FFT traces show the peak frequency of the instability to be near $f = \omega/2\pi \approx 30 \text{ kHz}$ or $\omega \sim 0.8\Omega_i$ for these conditions.

Furthermore, the FFT traces show that the amplitude of the instability is anticorrelated with the current. This suggests that these modes may not be related to current-driven phenomena. To confirm this, a comparison is made between the phase velocity of the instability and the parallel (i.e., field aligned) electron drift velocity.

In order for the mode to be a current-driven instability, it is expected that the phase velocity of the wave, $v_\phi = (\omega - k_y v_E)/k_z$, should be comparable to the parallel electron drift velocity, v_\parallel . Here, k_y and k_z are the azimuthal and longitudinal wave numbers, respectively, ω is the measured angular frequency of the instability and v_E is the $\mathbf{E} \times \mathbf{B}$ drift speed. The electron drift speed is $v_\parallel = j/n_0 e$; where j is the current density collected on Ring 3, which has a collecting area of $7.2 \times 10^{-4} \text{ m}^2$, n_0 is the electron density, and e is the electron charge. Preliminary measurements show that for the

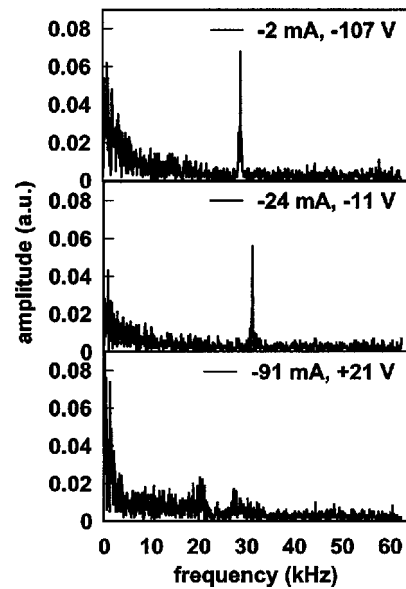


FIG. 1. FFT spectra of the floating potential on a Langmuir probe indicating the growth of the instability as a function of the current collected/bias voltage on Ring 3. The measurements show that the growth of the instability is anticorrelated with the current. The vertical axis represents the amplitude of the FFT in arbitrary units (a.u.).

observed instabilities $k_y \sim 70 \text{ m}^{-1}$ and $k_z \sim 8 \text{ m}^{-1}$; this gives the ratio $k_z/k_y \sim 0.11$.

At a current of $I_3 \approx 2 \text{ mA}$, the ratio of the parallel electron drift speed to the phase speed is $|v_\parallel/v_\phi| = 0.02$. By contrast, a key requirement to establish the current driven instability is that $|v_\parallel/v_\phi| \sim 1$. Thus, the experimental measurements suggest that for the parameters in ALEXIS, it is unlikely that this mode is a current driven mode.

In an additional attempt to characterize the instability, a Langmuir probe located 8 cm upstream from the rings is moved radially through the plasma. The amplitude of the instability, obtained from the FFT spectrum, is recorded as a function of position. This is done for several different currents (i.e., bias voltages) on Ring 3. The results of these measurements are shown in Fig. 2. Here, the instability is shown to be localized to the region in the plasma that coincides with the radial position of Ring 3. It is also noted that the data in Fig. 2 shows that the amplitude of the instability increases with decreasing collection current on Ring 3; this is consistent with the measurement shown in Fig. 1.

Additionally, it is shown in Fig. 3 that this region of the plasma where the instability reaches its maximum amplitude also corresponds to the region where the electric field strength as a function of the radial position is strongly varying. This gives rise to a region of the plasma with a sheared $\mathbf{E} \times \mathbf{B}$ flow. This provides good evidence that the observed instabilities may be related to the presence of sheared transverse flows in the plasma.

Of particular concern in this study is the presence of density gradients in the plasma. These gradients could provide a source of free energy to drive drift waves. A careful analysis of experimental measurements is required to determine whether drift waves are likely to grow for the conditions in ALEXIS. Figure 4 shows that the density gradient is

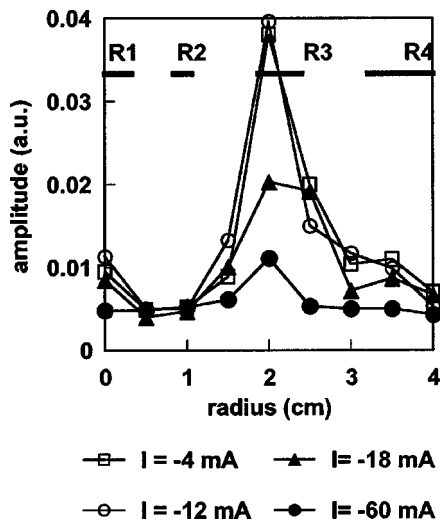


FIG. 2. Localization of the observed instability to the region near Ring 3. The thick black lines labeled R1–R4 indicate the spatial extent of each of the ring electrodes. This measurement is consistent with Fig. 2 in showing that the amplitude of the instability increases as the current collected by Ring 3 decreases.

a minimum under the conditions when the instability has its maximum amplitude (i.e., for minimum electron current on Ring 3). This provides an initial suggestion that the instability may not be correlated to the density gradient. However, a more detailed analysis is required to substantiate this measurement.

This is accomplished by computing an estimate for the growth rate of drift waves in the presence of a sheared transverse flow following methods in Refs. 20 and 29. This is shown in Eq. (1),

$$\gamma = - \frac{\sqrt{\frac{\pi}{2}} \left(\frac{\omega_{1R}^2}{|k_z v_{te}|} \right) (\omega_{1R} - \omega_{*e})}{(2(1 + b_s) \omega_{1R} - \omega_{*e})}. \quad (1)$$

Here, $b_s = (k_y C_s / \Omega_i)^2$, where C_s is the ion sound speed and Ω_i is the ion cyclotron frequency. The term $\omega_{1R} = \text{Re}[\omega$

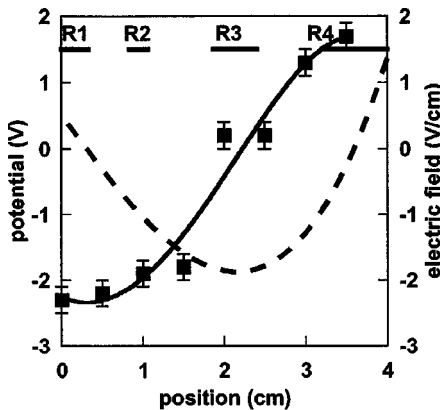


FIG. 3. Measurement of the plasma potential (solid squares) and computed electric field (dashed line). The plasma potential is measured using an emissive probe. The solid line is a fourth-order polynomial fit to the plasma potential measurements. The electric field is computed from the negative derivative of the potential curve fit. This measurement is taken when Ring 3 is drawing a low electron current.

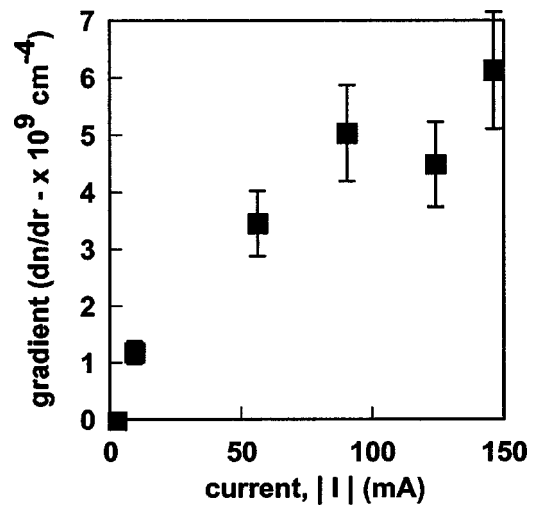


FIG. 4. Scaling of the density gradient (dn/dr) in the vicinity of Ring 3 with the magnitude of the electron currents (bias voltage) collected on Ring 3. As the current collected by the ring is decreased, the density profile in ALEXIS flattens.

$-k_y v_E]$ is the Doppler shifted frequency of the wave. The term ω_{*e} is the diamagnetic drift frequency and is computed using

$$\omega_{*e} = k_y v_{dr} = (k_y) \frac{k_B T_e}{eB} \left(\frac{1}{n} \right) \left(\frac{dn}{dr} \right). \quad (2)$$

The drift frequency is estimated to be $\omega_{*e} \sim 800$ rad/s. By contrast, the Doppler shifted wave frequency is $|\omega_{1R}| = 1.1 \times 10^6$ rad/s $\gg |\omega_{*e}|$. Using this fact in Eq. (1) with the knowledge that all of the remaining terms are positive definite leads to the result that, for the parameters used in the ALEXIS device for this investigation, the growth rate of drift waves is negative. This suggests that the instability observed in the ALEXIS device is not a drift wave.

With the aforementioned experimental results, it is possible to draw the following conclusions. First, the observed instability is not related to current driven phenomena. In fact, the amplitude of the instability grows with decreasing current. Second, the observed instability is not a drift wave. The frequency of the instability is much higher than the drift frequency. Third, the instability is localized to a region of the plasma in which the electric field strength is strongly varying—suggesting the presence of sheared flows.

To characterize the observed instability, consider the response of the plasma to both a field aligned current and a transverse flow. This response is parametrized by the term $R = k_y v_E / k_z v_{\parallel}$. Using the preliminary values for the ratio of transverse and parallel wave numbers given earlier gives an estimated value of $R \sim 70$. For cases $R \gg 1$, it has been shown that ion cyclotron waves can be driven unstable by velocity shear even in the absence of a field aligned current.^{17,18,34} These shear driven ion cyclotron modes prefer long azimuthal wavelengths³⁰ (i.e., low m numbers), which is the spectral characteristic of the observed instability.

At a radius $r = 2$ cm, the measured azimuthal wave number $k_y = m/r$ (where, m is the azimuthal mode number and r is the radius) suggests a mode number between 1 and 2.

Thus, another possible mechanism for this instability could be the Kelvin–Helmholtz (KH) mode. However, KH modes prefer high m -numbers^{31–33} and have no growth for $m = 1$. In addition, they are strongly Landau damped¹⁹ unless $k_z/k_y \sim 0$. Since the experimental observations give $k_z/k_y \sim 0.11$ and have low m numbers, it appears unlikely that the observed modes are due to the KH instability.

Considering this initial evidence, the results suggest that the observed instabilities are related to the presence of the sheared flow in the plasma. These measurements are consistent with prior observations of the inhomogeneous energy density driven (IEDD) instability.^{34,35} The IEDD instability is a velocity shear driven instability in the ion cyclotron frequency range.

At present, the IEDD instability has been observed in two experiments, a Q-machine³⁵ and a large volume plasma chamber.³⁴ This experiment, therefore, expands the range of experimental environments in which this new class of plasma instability has been observed. Given the recent importance of velocity shear driven phenomena to a wide variety of plasma systems, it is critical to develop both a theoretical and experimental base in which to explore many of these phenomena. The results reported in this letter provide evidence for the formation of the IEDD instability in ALEXIS. Upcoming experiments will seek to obtain more highly resolved measurements of the potential structure and make use of optical techniques to directly measure ion flows in the plasma.

In summary, low frequency waves in the ion cyclotron regime have been identified in a magnetized helium plasma column. The radial potential structure in the plasma is controlled using an array of four ring electrodes that are oriented perpendicularly to the axial magnetic field. An instability is observed in the plasma that is spatially localized at the radial position corresponding to Ring 3 and is correlated to the bias voltage (collected current) on that electrode. The preliminary evidence suggests that the instability is a transverse velocity shear driven ion cyclotron wave.

These measurements are contrary to results often obtained from toroidal fusion energy experiments in which flow shear is a signature of the transition to enhanced confinement regimes and a corresponding stabilization of low frequency modes even though shear represents a source of free energy. This indicates that there may be conditions under which velocity shear is a stabilizing agent as opposed to a destabilizing agent. Whether these conditions are specific to experimental devices or more general remains an outstanding issue. Clearly, additional physical mechanisms associated with toroidal plasma systems may play an important role and require further scrutiny.³⁶

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