Plasma Response to Strongly Sheared Flow

W. E. Amatucci, D. N. Walker, G. Ganguli, and J. A. Antoniades
Plasma Physics Division, Naval Research Laboratory, Washington, D.C. 20375

D. Duncan and J. H. Bowles
Sachs-Freeman Associates, Landover, Maryland 20785

V. Gavrishchaka and M. E. Koepke
Department of Physics, West Virginia University, Morgantown, West Virginia 26506
(Received 11 January 1996)

Laboratory observations of reactively driven plasma waves in the ion-cyclotron frequency range associated with a localized, transverse dc electric field are reported. This wave excitation occurs even when the field-aligned current is negligible, a situation often reported in the space plasma environment. The fluctuation spectrum is broadband in frequency and its peak depends on the magnitude of the dc electric field. Comparison with theory indicates that these waves result from a strong inhomogeneity in the energy density caused by sheared $\mathbf{E} \times \mathbf{B}$ flow. [S0031-9007(96)01143-X]

PACS numbers: 52.35.Fp, 52.35.Qz, 94.20.Bb, 94.30.Gm

We report the first laboratory observations of reactively driven ion-cyclotron waves associated with a highly sheared flow transverse to the magnetic field and negligible field-aligned current. Sufficiently strong sheared flow can generate a region of strong inhomogeneity in the energy density [1]. Convection of energy away from this region can give rise to plasma oscillations whose wavelength is related to the inhomogeneity scale length [1,2]. Since such conditions often arise in space [3–7], astrophysical [8], and laboratory [9–16] plasmas, a detailed knowledge of the plasma response to a strongly sheared flow is crucial for the analysis and interpretation of observations. In particular, during periods of intense solar activity, there is evidence of velocity shear buildup in the magnetosphere, especially in boundary layers [5,6] and the auroral region [3,7,17]. Since the magnetospheric plasma is essentially collisionless, the dissipation of this shear is generally achieved via collective effects which in turn can affect the spatial structure [18], plasma energization [4], and local transport properties [19]. The experimental investigation reported in this Letter is relevant to the understanding of such naturally occurring plasma processes.

The influence of velocity shear on plasma oscillations can be generally classified into two regimes, dissipative and reactive [2,4]. In the dissipative regime, low levels of shear can modify the dispersive properties of a homogeneous plasma and hence can affect the wave-particle interactions such as Landau damping or growth. In the reactive regime, a sufficiently strong shear can induce oscillations by creating neighboring regions with wave energy density of opposite sign. In the simultaneous presence of a magnetic-field-aligned drift and a transverse, localized, dc electric field, the plasma response can be categorized by the parameter $R \equiv k_\theta v_E / k_z v_d$ [20]. Here, (in cylindrical geometry) k_θ, k_z, v_E, and v_d are the wave-vector components and flows transverse (azimuthal) to and along the magnetic field, respectively. Small values of R (≤ 1) usually signify the dominance of the field-aligned drift and represent the dissipative regime. Large values of R ($\gg 1$) correspond to the reactive regime, in which ion-cyclotron waves can be driven unstable even in the absence of a field-aligned drift [1,2].

In the presence of velocity shear, the mode characteristics of ion-cyclotron waves can be significantly different [2,20] from the homogeneous case [21–23]. The dissipative regime, in which the combination of field-aligned and cross-field flows is important, was recently examined in a series of Q-machine experiments [9–11]. It was found that the threshold current for the ion-cyclotron instability decreased with increasing shear [11]. In addition, the mode frequency was observed to shift with the applied electric field strength, and the wave spectrum became broadband and spiky [9]. While these experiments investigated the dissipative effect of velocity shear, the reactive response, which is independent of field-aligned flow, was inaccessible to the experimental setup.

We report laboratory experiments designed specifically to investigate the reactive effects of a strongly sheared transverse flow. The experiments are conducted in the Naval Research Laboratory's Space Physics Simulation Chamber (SPSC), a device well suited for the investigation of space plasma processes. The SPSC is a 1.8 m diameter by 5 m long cylindrical vacuum vessel outfitted with a large-diameter microwave plasma source [24]. The parameters of the steady-state argon plasma are plasma density $n \approx 3.5 \times 10^7$ cm^{-3}, ion and electron temperatures $T_i \approx 0.05$ eV and $T_e \approx 1.0$ eV, uniform axial magnetic field $B = 40$ G, ion gyrofrequency $f_{ci} = 1.5$ kHz, ion gyroradius $\rho_i = 5$ cm, ion thermal

 0031-9007/96/77(10)/1978(4)$10.00

speed $v_{ti} \approx 5 \times 10^4$ cm/s, Debye length $\lambda_D \approx 0.2$ cm, neutral density $n_n \approx 6 \times 10^{11}$ cm^{-3}, and plasma column diameter and effective length are 50 cm and 2 m, respectively. Wave and bulk plasma parameters are measured with Langmuir probes [25] and emissive probes.

Figure 1(a) depicts the experimental setup. Sheared azimuthal flow is induced by a controllable, radially localized, dc electric field located within the cylindrical SPSC plasma column. This is accomplished with a grid structure made from concentric, coplanar, conducting ring electrodes. This multiringed electrode (MRE) consists of 11 circular rings constructed from 3 mm diameter brass rods. The innermost and outermost rings have diameters of 10 and 30 cm, respectively and the center-to-center ring spacing is 1 cm. The MRE diameter is several ρ_i smaller than the plasma column diameter and is centered on the column axis 2 m from the microwave plasma source. The MRE rings are divided into inner and outer groups by electrically connecting each ring within a group. Application of different potentials to the inner and outer groups modifies the radial structure of the plasma potential, creating a localized, dc electric field. Particles entering the plasma column from the microwave source experience an adiabatic increase in the electric field to its peak value, leading to an azimuthal drift within a cylindrical shell (approximately one ion gyroradius thick) as shown in Fig. 1(b). An equilibrium distribution of thermal particles with $\mathbf{E} \times \mathbf{B}$ drift can be maintained for such localized electric fields [2,26]. Energy analyzer [27] measurements indicate no unusual energization of the ions following application of the radial dc electric field. The mean-free path for ion-neutral collisions [28] is comparable to the plasma column length; therefore collisional effects are minimal.

Figure 2 shows a typical cylindrically symmetric plasma potential profile (circles) and the associated electric field (triangles) produced by the MRE as a function of radial position. The seven outermost rings are biased to +20 V with respect to chamber ground and others are biased to −10 V. Plasma potential is measured with an emissive probe located 14.5 cm axially in front of the MRE. The radial dc electric field is localized to the annular region $4 < r < 11$ cm and has a peak amplitude of 0.6 V/cm. Measurements made at various axial locations in front of the MRE indicate that the electric field extends at least 88 cm into the plasma column and remains roughly constant. The electric field strength is controlled primarily by the potential applied to the outer ring group and maximizes at $E \approx 0.75$ V/cm.

In addition to the inhomogeneity in the azimuthal flow, application of potential to the MRE induces low levels of magnetic-field-aligned current within the plasma column. The relative drift velocity between the electrons and the ions has been determined using a directional Langmuir probe technique [29,30] and from measurement of the current collected by the MRE. The directional Langmuir probe technique involves fitting a drifting Maxwellian to differentiated current-voltage characteristics taken with the probe first facing upstream, then downstream, within the drifting electron population. In the second method, the parallel drift velocity of the electrons is determined from a measurement of the current collected by the inner and outer MRE sections along with spatially resolved Langmuir probe measurements of plasma density. The parallel electron drift velocity if found by using the expression $v_d = j/n_0 e$, where j is the current density, n_0 is the average local plasma density, and e is the electron charge. For the plasma conditions illustrated in Fig. 2, both techniques indicate that $v_d \approx 3v_{ti}$.

When an electric field of sufficient magnitude is imposed, waves in the ion-cyclotron frequency range can be detected from oscillations in the ion-saturation current collected by Langmuir probes and from fluctuations in the electron current collected by the MRE sections. Figure 3 shows probe measurements of mode amplitude as a function of radial position with the inner and outer MRE ring groups biased to −10 and 40 V, respectively. This measurement indicates that the waves are localized to radii corresponding to the cylindrical shell of drifting plasma with the peak mode amplitude occurring at $r \approx \pm 10$ cm.

The transverse and field-aligned wave-vector components $k_\theta = 2\pi/\lambda_\theta$ and $k_z = 2\pi/\lambda_z$ have been determined using a cross-correlation technique [31] to

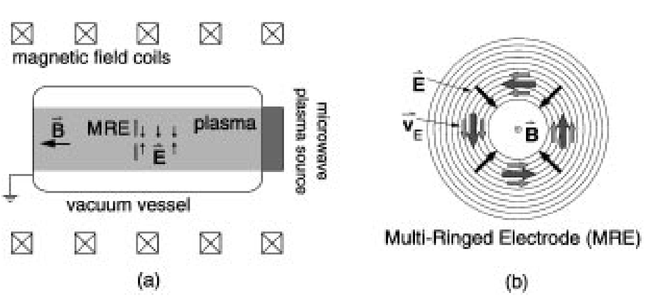

FIG. 1. Schematic diagram of experiment (a) showing location of MRE and (b) front view of MRE depicting the rings, transverse electric field, and azimuthally sheared flow.

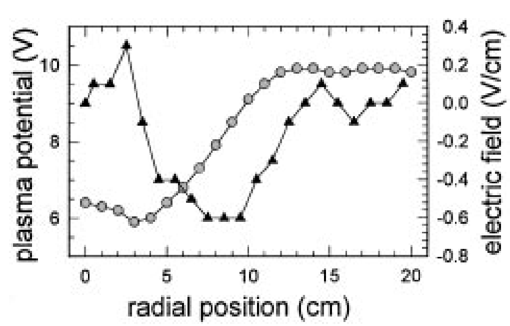

FIG. 2. Plasma potential (circles) and electric field (triangles) as a function of radius with the four inner MRE rings biased to −10 V and seven outer rings biased to +20 V.

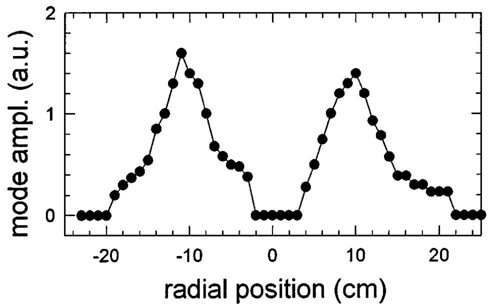

FIG. 3. Mode amplitude vs radial position with the inner MRE ring group biased to -10 V and the outer group biased to $+40$ V. Peak mode amplitude occurs at $r \approx \pm 10$ cm.

measure the phase difference $\Delta\phi$ between ion-saturation current fluctuations simultaneously obtained from pairs of Langmuir probes. In each case, three coplanar Langmuir probes with identical tips are unequally spaced (to reduce the possibility of aliasing) along the azimuthal or axial direction. For the measurement of azimuthal wave number, the values of $\Delta\phi$ are consistent with an $m = 1$ mode with $k_\theta = 0.11 \pm 0.003$ cm^{-1} propagating in the $\mathbf{E} \times \mathbf{B}$ direction. The measurement of the axial wave number indicates propagation away from the plasma source with $k_z = 0.013 \pm 0.001$ cm^{-1}.

The normalized wave amplitude is plotted as a function of v_E/v_{ti} in Fig. 4. The wave amplitude increases with the magnitude of v_E ($\equiv |E/B|$) until it saturates at $\delta n/n \approx 15\%$, when v_E exceeds $30 v_{ti}$. A sample wave spectrum acquired from a Langmuir probe located 75.4 cm from the MRE is inset in Fig. 4. The fluctuation spectrum is broadband ($\delta f/f \approx 30\%$) and spiky which is typical of inhomogeneous energy-density driven (IEDD) waves [9,10,32]. Shown as a solid line is the IEDD instability growth rate theoretically predicted using SPSC plasma parameters, which indicates a large threshold electric field ($E \approx 0.25$ V/cm). It is interesting to note that the qualitative behavior of the linear growth rate and the saturated wave amplitude is similar and the experimentally determined value of the threshold occurs at a large magnitude of electric field ($E \approx 0.4$ V/cm).

Theoretical analysis indicates that for the experimental conditions, the change in the mode frequency $\Delta f = (f - f_0)/f_{ci}$ scales as the Doppler shift due to the cross-field drift, where f_0 is the mode frequency at threshold. In Fig. 5, Δf is plotted as a function of v_E/v_{ti}. As v_E/v_{ti} is increased from 20 to 40, Δf increases from 0 to 1.1. In this range of v_E, the real frequency upshifts from $1.5 f_{ci}$ to $2.6 f_{ci}$. We compare the experimental values of Δf with the calculated Doppler shifts in cylindrical and slab geometries. For our parameters, the cylindrical geometry results in an azimuthal drift which is smaller than v_E, scales as $E^{1/2}$, and leads to good agreement with the experiment. The upshifting of frequency with increasing v_E in the reactive regime is in sharp contrast to the corresponding down-shifting in the dissipative regime predicted theoretically and observed in the Q-machine experiments [9].

Near the threshold, the field-aligned drift v_d is approximately $1.1 v_{ti}$ ranging to $v_d \approx 3.5 v_{ti}$ at the largest values of applied voltage. The predicted critical electron drift velocity of the current-driven-electrostatic ion-cyclotron (CDEIC) instability for SPSC plasma parameters is $15 v_{ti}$. Thus, the ion-cyclotron waves are observed at values of magnetic-field-aligned current density that are 93% below the predicted CDEIC threshold. While total elimination of v_d is experimentally difficult, theoretical analysis shows that the observed level of v_d is inconsequential to the mode characteristics. Calculations for experimental conditions indicate that the threshold v_E for the Kelvin-Helmholtz instability is around $2 v_{ti}$ and the fastest growth occurs for $k_z/k_\theta = 0$. Hence, it is unlikely that the fluctuations result from the Kelvin-Helmholtz instability since there is an observed threshold at large electric field ($v_E \approx 20 v_{ti}$) and the value of k_z/k_θ is significantly larger than zero. For

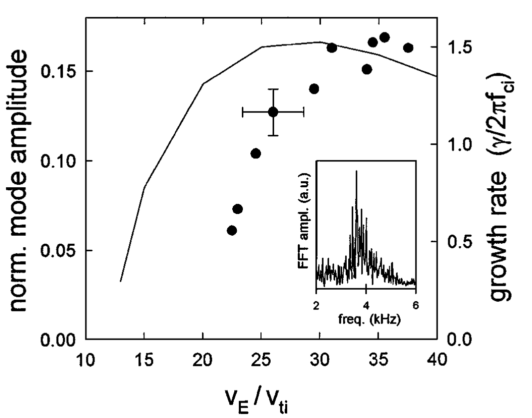

FIG. 4. Normalized mode amplitude $\delta n/n$ (circles) and theoretically predicted IEDD growth rate (solid line) as a function of increasing electric field strength. Typical wave spectrum is inset.

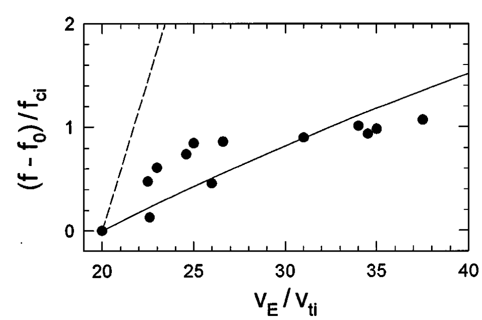

FIG. 5. Experimentally measured (circles) and theoretically calculated change in mode frequency as a function of increasing electric field strength. Solid and dashed lines correspond to cylindrical and slab geometry, respectively.

all values of electric field strength at which fluctuations are observed, the azimuthal drift significantly exceeds the transverse wave phase velocity (ω_r/k_θ) which is a necessary condition for reactive growth [1,2] and which makes the centrifugally driven flute mode unlikely [33], especially since k_z/k_θ is large. For experimentally determined values of k_θ, v_E, k_z, and v_d it is found that $R \approx 100$.

The mode has been identified as the reactively driven IEDD instability based upon the consistency between experimentally observed mode characteristics and those predicted by theory. Previous experimental studies in different plasma parameter regimes including a transverse electric field have also reported significant changes in observed ion-cyclotron mode properties [12–14], although detailed measurements of some mode characteristics and comparison with theory were not provided. The results presented in this Letter indicate that sheared plasma flow resulting from inhomogeneous, transverse electric fields can play an important role in the generation of plasma waves and may have significance to the interpretation of ionospheric and magnetospheric satellite data. An increasing body of *in situ* data finds correlation between wave activity and localized transverse electric fields. Among the latest of such results are data from the Freja satellite in which intense, narrow, transverse electric fields ($\approx$1 V/m) are observed in association with black aurora along with low frequency, broadband electrostatic waves [3]. Since significant field-aligned currents are lacking in these regions [3], localized, transverse electric fields may play an important role in wave destabilization. Such wave activity can contribute to the transverse ion heating [4] which is necessary for the formation of ion conics and thermal ion outflow events in the ionospheric plasmas.

This work was supported by the Office of Naval Research. We gratefully acknowledge Dr. R. Meger for his critical reading of the manuscript and numerous stimulating discussions with Dr. B. Ripin. W. E. A. acknowledges the receipt of a National Research Council Postdoctoral Fellowship.

[1] G. Ganguli, Y. Lee, and P. Palmadesso, Phys. Fluids **28**, 761 (1985).
[2] G. Ganguli, Y. Lee, and P. Palmadesso, Phys. Fluids **31**, 823 (1988).
[3] G. Maklund, L. Bloomberg, C. Falthammar, and P. Lindqvist, Geophys. Res. Lett. **21**, 1859 (1994).
[4] G. Ganguli *et al.*, J. Geophys. Res. **99**, 8873 (1994); G. Ganguli, in *Cross-Scale Coupling in Space Plasmas*, Geophysical Monograph Vol. 93, edited by J. Horowitz, N. Singh, and J. Burch (American Geophysical Union, Washington, DC, 1995), p. 23.
[5] P. Song, R. Elphic, C. Russell, J.Gosling, and C. Ca, J. Geophys. Res. **95**, 6375 (1990).
[6] H. Romero, G. Ganguli, P. Dusenbery, and P. Palmadesso, Geophys. Res. Lett. **17**, 2313 (1990).
[7] F. Mozer *et al.*, Phys. Rev. Lett. **38**, 292 (1977).
[8] Y. Lau, C. Lin, and J. Mark, Proc. Natl. Acad. Sci. U.S.A. **73**, 1379 (1976).
[9] M. Koepke, W. Amatucci, J. Carroll III, and T. Sheridan, Phys. Rev. Lett. **72**, 3355 (1994).
[10] M. Koepke *et al.*, Phys. Plasmas **2**, 2523 (1995).
[11] W. Amatucci *et al.*, Geophys. Res. Lett. **21**, 1595 (1994).
[12] D. Jassby, Phys. Fluids **15**, 1590 (1972).
[13] N. Sato, M. Nakamura, and R. Hatakeyama, Phys. Rev. Lett. **57**, 1227 (1986).
[14] E. van Niekirk, P. Krumm, and M. Alport, Plasma Phys. Controlled Fusion **33**, 375 (1991).
[15] H. Berk *et al.*, Phys. Rev. Lett. **22**, 876 (1969).
[16] M. Yamada and D. Owens, Phys. Rev. Lett. **38**, 1529 (1977).
[17] R. Tsunoda *et al.*, J. Geophys. Res. **94**, 15 290 (1989).
[18] D. Winske and N. Omidi, J. Geophys. Res. **100**, 11 923 (1993); M. Fujimoto and T. Terasawa, J. Geophys. Res. **100**, 12 025 (1995); H. Romero and G. Ganguli, Geophys. Res. Lett. **21**, 645 (1994).
[19] S. Ganguli and P. Palmadesso, J. Geophys. Res. **92**, 8673 (1987).
[20] G. Ganguli *et al.*, in *Physics of Space Plasmas, 1988*, SPI Conference Proceedings and Reprint Series, edited by T. Chang, G. Crew, and J. Jasperse (Scientific Publishers, Cambridge, MA, 1989), Vol. 8, p. 231.
[21] W. Drummond and M. Rosenbluth, Phys. Fluids **5**, 1507 (1962).
[22] M. Kindel and C. Kennel, J. Geophys. Res. **76**, 3055 (1971).
[23] R. Motley and N. D'Angelo, Phys. Fluids **6**, 296 (1963).
[24] J. Bowles *et al.*, Rev. Sci. Instrum. **67**, 455 (1996).
[25] W. Amatucci *et al.*, Rev. Sci. Instrum. **64**, 1253 (1993).
[26] D. Cai *et al.*, Phys. Fluids B **2**, 75 (1990); P. Pritchett, Phys. Fluids B **5**, 3770 (1993).
[27] I. Katsumata and M. Okazaki, Jpn. J. Appl. Phys. **6**, 123 (1967); M. McCarrick *et al.*, Rev. Sci. Instrum. **56**, 1463 (1985).
[28] A. Phelps J. Phys. Chem. Ref. Data **20**, 557 (1991).
[29] J. Carroll III *et al.*, Rev. Sci. Instrum. **65**, 2991 (1994).
[30] M. Guyot and Ch. Hollenstein, Phys. Fluids **26**, 1596 (1983).
[31] D. Smith, E. Powers, and G. Caldwell, IEEE Trans. Plasma Sci. **2**, 261 (1974).
[32] K. Nishikawa, G. Ganguli, Y. Lee, and P. Palmadesso, Phys. Fluids **31**, 1568 (1988).
[33] J. Chen, A. Sen, and S. Migliuolo, Phys. Fluids B **4**, 512 (1992).