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Study of Drift Wave Turbulence by Microwave Scattering in a Toroidal Plasma

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ABSTRACT

A study of drift wave turbulence by microwave scattering technique was carried out in a toroidal plasma confinement device, the FM-1 spherator. The principal results are; (a) Observation of the linear dispersion relation of drift waves in the high magnetic shear condition. The linear dispersion relation is followed up to weak turbulence state ($\gamma \lesssim \omega$). (b) An experimental demonstration of the stabilization of the drift waves with an increase of the shear strength. In particular, the ion mass dependence of the observed marginal stability criterion for drift waves ($\omega \simeq \omega_*$) was in reasonably good agreement with theoretical expectations. Further, very low frequency ($\omega << \omega_*$) fluctuations were enhanced when the shear strength was lowered. (c) A detailed study of the behavior of drift waves in a weak shear condition where a state of isotropic turbulence was observed. The turbulent density fluctuations showed a strong dependence on frequency, but no dependence on wave number (somewhat in sharp contrast to theoretical expectations). The possible dependence of the anomalous loss process on the observed drift wave turbulence is also discussed.

1. INTRODUCTION

There have been intensive experimental studies of drift wave turbulence in linear and toroidal plasma devices. The purpose of these studies was to identify the cause of low frequency drift wave fluctuations and to examine the activity of the drift wave turbulence in conjunction with the observed apparent anomalous particle and heat diffusion processes. For example, in the past, considerable attention has been payed to the fluctuation studies in the spherator devices [1 - 10]. Here we report on the study of drift wave turbulence in the FM-1 spherator by a microwave scattering technique.

We believe that the present experiment is the first experimental identification and study of drift wave turbulence by microwave scattering techniques in a tenuous plasma, where traditionally Langmuir probe measurements have been widely used. One advantage of using the microwave scattering technique is that a simultaneous measurement can be made of both the ω and k spectrum, where ω and k are the frequency and the wave number of the drift wave. Secondly, we can eliminate the physical insertion of the probe inside the plasma which may cause local inhomogeniety in the plasma density resulting in additional excitation of low-frequency fluctuations. Thirdly, we can clarify doubts about the sensitivity of probe of which the tip size is comparable to the wave length. Thus, the previous experimental studies which were carried out mainly by using Langmuir probes will be reexamined in the light of the present experiment in order to see whether or not any significant misunderstanding was introduced by insertion of probes.

The recent development of high power microwave tubes with extremely low noise level at low frequencies ($\lesssim$ 1 MHz) has made this scattering experiment possible in low density plasmas ($n_e \simeq 5 \times 10^{11} cm^{-3}$), although similar techniques have been used mainly to study high frequency fluctuations in high density plasma such as the density fluctuations associated with ion-accoustic waves in current-carrying plasmas [11, 12].

The principal objectives of the present experiment are: (a) to show that one can measure the dispersion relation of low-frequency drift waves by microwave scattering technique alone; (b) to demonstrate the shear stabilization of the drift waves, and specifically to examine whether or not the ion mass dependence of the stability criterion is in agreement with theoretical predictions; (c) to study the behavior of the drift wave frequency and wave number power spectrum in the fully developed turbulent regime in plasmas produced with various different heating schemes (such as microwave dc discharges, Ohmic heated discharges and neutral beam injection heated discharges), and (d) to give some discussions on the possible dependence of the anomalous (particle and energy) confinement properties of plasmas (produced with various different heating schemes) on the level of drift wave turbulence.

The paper is organized as follows: In Section 2, the experimental arrangement, the plasma conditions, and the properties of magnetic field configurations are discussed. The experimental results are presented in Section 3. Some discussions about strong turbulence and anomalous plasma transport are carried out in Section 4. A brief summary of the experimental results and our conclusions are given in Section 5.

2. EXPERIMENTAL ARRANGEMENT

The FM-1 spherator has a levitated superconducting coil and the plasmas are confined with the combination of the poloidal magnetic field B_P produced by the superconducting coil current I_P, a magnetic surface shaping vertical field coil current I_E, and a toroidal field B_T produced by the current I_T along the axisymmetric axis [1]. In the present experiment the superconducting coil was excited with 275 kAT and the toroidal field was varied to produce the different magnetic shear values. The average value of the magnetic field strength B is 3.0 ~ 3.5 kG and the ratio B_T/B_P is 1/5 ~ 1/7 with the maximum toroidal field strength. In other words, the main magnetic field component is in the poloidal direction in contrast to that in the tokamak. For convenience, in the following we use the natural (ψ, χ, ϕ) coordinates, where ψ-direction is parallel to the density gradient, χ-direction is along the poloidal field direction B_P, and ϕ-direction is parallel to the toroidal field component B_T.

Figure 1 is a schematic block diagram of the experimental arrangement. The incident microwave power was supplied by a Varian VKQ2420G2 extended interaction oscillator. This newly developed Varian tube was very stable both in frequency and power output. Further the output of this tube has extremely low noise level even in the very close neighborhood of its transmitting frequency. The tube was capable of delivering a maximum output power of about 100 W. However in our experiment the tube was operated at an output power level of about 6 W and this further reduced the noise level in the vicinity of the transmitting frequency. The incident microwave power from the transmitter was beamed on to the plasma by a horn antenna (gain $\gtrsim$ 25 db) placed inside the vacuum vessel of the FM-1 spherator. The incident frequency $f_I \simeq 33.5$ GHz. After correcting for the losses due to the transmission waveguides, vacuum windows and the high voltage safety insulation breaks (between the spherator vacuum vessel and the 8-mm microwave transmitter-receiver system), the effective incident power $P_I \simeq 0.2$ W. The scattered signal was picked up by another identical antenna also placed inside the vacuum chamber. We have installed an array of horn antennas inside the vacuum chamber so that we can make scattering measurements at scattering angles: $\theta_\phi \simeq 45°$, $60°$, and $75°$ keeping $\vec{k} = (\vec{k}_I - \vec{k}_s)$ parallel to the direction of propagation of the drift waves (i.e., the ϕ-direction); $\theta_\psi \simeq 30°$ with $\vec{k}$ along the radial direction (i.e., the ψ-direction); and $\theta_\chi \simeq 15°$ with $\vec{k}$ along the poloidal magnetic field direction (i.e., the χ-direction). Here θ is one half of the angle between the incident wave vector $\vec{k}_I$ and the scattered wave vector $\vec{k}_s$. The wave number k of the drift wave that is responsible for the scattering is given by $k = |\vec{k}_I - \vec{k}_s| = 2k_o \cos\theta$, where $k_o = |\vec{k}_I| = |\vec{k}_s|$. The scattering volume as defined by the common intersection of the transmitter and the receiver horn antenna patterns was chosen around the location of the maximum density gradient. In the homodyne detection system of Fig. 1, the scattered signal was mixed with a larger reference signal directly from the transmitter at the balanced crystal mixer. The difference signal from the mixer [i.e., the scattered signal at $f = |f_s - f_I|$] was then amplified (by the broad band amplifier) and finally Fourier analyzed (by the spectrum analyzer). The receiver was calibrated by sending a known amount of amplitude modulated microwave power. The modulation frequencies of 3 kHz and 20 kHz were used in the calibration and the receiver sensitivity was the same for both these modulation frequencies. The typical scattered power level was in the range of 10^{-4} to 10^{-6} W and the noise level of the homodyne detection system mainly at low frequencies was about 10^{-7} W.

The general theory of the scattering of electromagnetic waves from the electron density fluctuations in a plasma can be found in Refs. [13, 14]. Usually in any scattering experiment what one measures is the amount of electromagnetic wave power that is scattered into a narrow frequency interval $\delta\omega$ which is determined by the frequency band width of the receiver system [i.e., in our experiment $(\delta\omega/2\pi) \approx 2$ kHz is the band width of the spectrum analyzer]. Since the scattered power is proportional to the square of the electron density fluctuations, we find that it is useful in presenting our experimental results to define $(\delta n/n)^2_\omega$ and $(\delta n/n)^2_o$ as

$$\left(\frac{\delta n}{n}\right)^2_\omega = \int_{\omega - \delta\omega/2}^{\omega + \delta\omega/2} d\omega \left[\frac{\delta n(\omega)}{n}\right]^2 , \qquad (1)$$

and .

$$\left(\frac{\delta n}{n}\right)_o^2 = \int_{-\infty}^{\infty} d\omega \left[\frac{\delta n(\omega)}{n}\right]^2 , \qquad (2)$$

respectively. In Sections 3, 4, and 5 we will consistently use the definition of Eq. (1) in describing the observed frequency power spectrum of the scattered radiation; while the definition of Eq. (2) will be used both in comparing the level of fluctuations as obtained by microwave scattering with that obtained by probe and in making estimates of the anomalous diffusion coefficient. We wish to point out that in our experiment the scattering measurements were done only at discrete values of $\vec{k} = \vec{k}_I - \vec{k}_s$ and the angular resolution of the antennas were such that $(\delta k/k) \approx 1/5$. Since in the strong turbulence regime the fluctuation spectrum is fairly isotropic in $k_\perp$ space with a width $\Delta k_\perp$ of the order of $k_\perp$, we estimate that the total (i.e., after a k-space integral) fluctuation level $\delta n/n$ is approximately given by $(\delta n/n)^2 \approx (\Delta k_\perp/\delta k)^2 (\delta n/n)_o^2 \approx 5^2 (\delta n/n)_o^2$. We emphasize that this is only a rough estimate of the total fluctuation level in the strong turbulence regime. Because of mechanical problems it proved impossible for us to experimentally obtain the entire k-spectrum of the fluctuations [an information that is needed to obtain more accurate value of the total fluctuation level].

In order to compliment our study of the density fluctuations associated with drift waves by microwave scattering, we have also monitored these density fluctuations by a movable Langmuir probe. The axis of the probe was in the radial direction. The tip of the Langmuir probe was a tungsten cylindrical wire of diameter 0.25 mm with an exposed length of 1 mm. This probe was also used to measure the radial density profile and the electron temperature. The average electron density was measured with a 4-mm microwave interferometer. The electron temperature T_e was also measured both by laser Thomson scattering and by spectroscopic measurements (i.e. determination of T_e from the line intensity ratios CIII 4647 Å/CIII 2297 Å and CIII 4647 Å/CII 4267 Å). The ion temperature T_i was measured spectroscopically (i.e., from the Doppler broadening of H_β and He II 4686 Å lines).

In the present experiments we have utilized plasmas produced by three different heating methods: microwave dc discharges, Ohmic heated discharges, and neutral beam injection heated discharges.

The dc discharges were produced by applying 1 kW dc x-band (i.e., 10.5 GHz) microwave power. The gases used were hydrogen, helium, neon, argon, and xenon with a filling pressure in the range 1×10^{-6} to 5×10^{-6} Torr. In these discharges the initial breakdown occurred by electron cyclotron resonance. The average electron density $n \simeq 2 \times 10^{11}\ cm^{-3}$, the electron temperature $T_e \simeq 2$ to 5 eV and the ion temperature $T_i \simeq 2$ eV. Most of our measurements were done in these dc microwave discharges. These discharges are convenient for making detail measurements of the scattered frequency and wave number power spectrum because of the steady state dc nature of the operation.

The Ohmic heated discharges were produced by exciting a plasma current inductively in the poloidal direction in a pre-ionized plasma [5, 15]. The preionized plasma (of $n \simeq 5 \times 10^{11}\ cm^{-3}$, $T_e \simeq 5$ eV and $T_i \simeq 2$ eV) was produced by using a pulsed (200 msec)

10.5 GHz microwave power. Here again the gases used were hydrogen, helium, neon, argon, and xenon with a filling pressure in the range 0.5×10^{-5} to 2×10^{-5} Torr. After the microwave power was turned off the Ohmic heating current of about 150 kA with one cycle at 500 Hz was drawn inductively in the poloidal direction. Since the preionized plasma was not fully ionized, the electron density increased from about 5×10^{11} cm^{-3} to about 5×10^{12} cm^{-3} and the electron temperature increased from about 5 eV to about 50 eV during the Ohmic heating pulse. The details of these n and T_e measurements can be found in Ref. [15].

We have also made some studies of the drift wave turbulence when a pulsed (10 msec) neutral hydrogen beam of about 75 kW at 15 kV was injected into a dc microwave target hydrogen plasma. In the neutral beam heating experiments, the electron temperature increased from about 5 eV to 40 eV during the first few milliseconds of injection and decayed slowly thereafter, while the electron density increased monotonically from about 5×10^{11}cm^{-3} to about 5×10^{12}cm^{-3} during the entire 10 msec duration of the neutral beam pulse [16].

We will now give some description of the magnetic field configuration, the plasma conditions (i.e., the present experimental parameter range), and the possible sources of free energy for the drift wave turbulence. The magnetic field configuration used in the experiment is shown in Fig. 1. As shown in Ref. [2] this field configuration with $I_T/I_P \lesssim 1$ is mainly a shear stabilization configuration for drift waves. The shear length L_s is defined by the generalized shear formula [8]

$$1/L_s = \frac{2\, B_P B_T}{B^2}\, \nabla\psi\ \ \ell n\, B_P R \ , \tag{3}$$

where R is the radial distance from the axisymmetric axis and $\nabla\psi$ is the component of the spatial gradient perpendicular to the magnetic surfaces. When $I_T/I_P = 1$, $L_s = 0.4 \sim 0.5$ m at the inside horizontal plane (i.e., close to the toroidal field coils) and at the outside horizontal plane $L_s = 1.5$ m. Thus the average shear length $\langle L_s \rangle$ is about 1 m for $I_T/I_P \simeq 1$. When the value of I_T/I_P is reduced to 0.2 the average shear length increases up to about 5 m. The empirical relation between shear strength and anomalous particle and heat transport was reported in a previous paper [3,4]. The anomalous particle and heat diffusion coefficients D and K are approximately given by

$$D = C \left\langle \frac{L_s}{a} \right\rangle \frac{\kappa T_e}{16\, eB} \ , \tag{4}$$

and

$$K \approx (3 - 5) D \ , \tag{5}$$

respectively, with $C = 1/400 - 1/800$ for $T_e \gtrsim 2$ eV, and the associated fluctuations of $(\delta n/n) \sim 5\%$. Here a is the density gradient scale length. It must be noted that in Ref. [3] the observed density fluctuations depended very sensitively on both the magnitude and sign of $\eta_e = [(d\ \ell n\ T_e/dr)/(d\ \ell n\ n/dr)]$.

It is now physically instructive to examine which of the possible types of drift modes (i.e., collisional, collisionless, and trapped-electron modes) are the likely candidates for our experimental parameter range of $5 \times 10^{10} \lesssim n \lesssim 5 \times 10^{12} cm^{-3}$, $2 < T_e < 30$ eV, and $T_i \simeq 2 - 5$ eV. The relevant parameters for identifying the cause of drift wave turbulence in the present experiment are: (a) the collisionality parameter ν_{eff}/ω_{be}, and (b) T_e/T_i. Here $\nu_{eff} \approx \nu_e/\varepsilon$ is the effective collision frequency for scattering a trapped electron out of the trapped region, ν_e is the electron collision frequency, $\varepsilon \approx \Delta B/B$ is the magnetic mirror ratio, and ω_{be} is the electron bounce frequency between mirror trapping. For our experimental conditions $0.1 \lesssim \nu_{eff}/\omega_{be} \lesssim 2$ and $3 \lesssim T_e/T_i \lesssim 10$. Therefore, collisional drift waves, collisionless drift waves, and collisional trapped-electron modes are possible candidates. In the first order approximation, the real part of the dispersion relation is the same for all these three types of drift waves, and this is given by

$$\omega \simeq \omega_* \, I_o(b) \; e^{-b}/[I_o(b)e^{-b} - 1 - T_i/T_e] \quad , \qquad (6)$$

where $\omega_* = (\kappa \, T_e k_\phi/e\,Ba)$ is the electron diamagnetic drift frequency, and $b = (k_\perp \rho_i)^2/2$. Here ρ_i is the ion Larmor radius. However, the imaginary part of the dispersion relation of these three types of drift waves are entirely different. This is because the sources of free energy that are responsible for their growth rates are different. Following the simplified formulas given in Refs. [17-19], in the first order approximation the normalized growth rates of the collisional drift waves, collisionless drift waves, and trapped electron modes are given by

$$(\gamma/\omega) \approx \frac{k_\parallel^2}{k_\perp^2} \frac{\Omega_e^2}{\omega_*} \frac{m_e}{m_i} \frac{1}{\nu_e}$$

$$(\gamma/\omega) \approx \frac{\sqrt{\pi}}{k_\parallel} \frac{\omega_*}{v_e} (1 - \eta_e/2)$$

and

$$(\gamma/\omega) \approx \sqrt{\varepsilon}\,\frac{\omega_*}{\nu_{eff}}\,(b + 0.5\,\eta_e) \quad , \qquad (7)$$

respectively. Here $k_\parallel$ is the parallel wave length, $k_\perp$ is the perpendicular wave length, m_e is the electron mass, m_i is the ion mass, Ω_e is the the electron cyclotron frequency, v_e is the electron thermal velocity. Although a more detailed discussion of these drift modes (including curvature, radial structure, connection length) can be found elsewhere, the essential physical mechanisms are adequately described in Eq. (7).

The effect of shear on these drift waves have been treated with different models. The approximate criterian for the shear stabilization of long wavelength (i.e., $k_\perp \rho_i \lesssim 1$) drift modes and in particular the ion mass dependence of the stability condition may be written [20,21]

$$\frac{a}{L_s} \gtrsim (m_e/m_i)^{1/2 - 1/3}\, f\,(L_{mfp}/a, \eta_e, T_e/T_i) \quad , \qquad (8)$$

where L_{mfp} is the mean free path of electrons, a is the scale length of the plasma, and $\eta_e = [(d\ \ell n\ T_e/dr)/(d\ \ell n\ n/dr)]$. Although f is a complicated function of these arguments, it is expected that f is of the order of unity and is weakly dependent on these parameters.

3. EXPERIMENTAL RESULTS

Plasmas produced by different heating schemes were utilized to investigate the different aspects of magnetic shear stabilization mechanism. For example, (1) a detailed study of the ω and k power spectrum of the scattered radiation for different shear values and the ion mass dependence of the marginal stability condition were carried out in microwave dc discharge plasmas; and (2) strong turbulence was studied under various conditions in plasmas produced by different heating schemes (such as microwave dc discharges, Ohmic heated discharges, and neutral beam injection heated discharges). First we discuss our study of drift waves in microwave dc discharge plasmas.

In the microwave dc discharge plasmas $n \approx 2 \times 10^{11} cm^{-3}$, $T_e \approx 2$ to 5 eV, and $T_i = 2$ eV. As shown in Fig. 2, with strong shear ($I_T/I_P \approx 1$, i.e., $\langle L_s \rangle \sim 50$ cm) the low-frequency drift-wave fluctuations were observed only around a scattering angle $\theta_\phi \approx 60°$ corresponding to $k_\phi \rho_i = 0.5$ but no scattered signals were observed at scattering angles $\theta_\phi \approx 75°$ (corresponding to $k_\phi \rho_i \approx 0.25$), $\theta_\phi \approx 45°$ (corresponding to $k_\phi \rho_i \approx 0.75$) and $\theta_\psi \approx 30°$ (corresponding to $k_\psi \rho_i \approx 0.87$). This data was taken in a helium plasma. The observed frequency spectrum is sharply peaked at $\omega/2\pi \approx 20$ kHz with a half width $\Delta\omega/\omega \approx 1/4$. In order to compliment our microwave scattering measurements we have also carried out measurements of the drift wave spectrum with the aid of a Langmuir probe. A typical spectrum as seen by the probe is also shown in this figure. A radial scan of the fluctuation level was also carried out with the aid of this movable probe. It was found that the drift wave fluctuations were localized in the region of the maximum density gradient. As seen from Fig. 2(b), these fluctuations were localized in a radial distance $\Delta r \approx \pm 0.5$ cm. The density gradient scale length $a \approx 7$ cm and the ion Larmor radius at the location of the maximum density gradient is about 0.3 mm. The frequency spectrum as observed by the Langmuir probe is similar to that obtained by microwave scattering at a scattering angle $\theta_\phi \approx 60°$ corresponding to $k_\phi \rho_i \approx 0.5$. However, the half width $\Delta\omega/\omega$ of the spectrum obtained by the probe is slightly larger than that of the spectrum obtained by microwave scattering. The magnitude of the fluctuation level $(\delta n/n)_p$ as measured by the probe is about 5%, and this is in reasonable agreement with the average fluctuation level $(\delta n/n)_o$ of about 2% as measured by microwave scattering. These results show that: (1) The dispersion of the excited fluctuations is well defined in the high magnetic shear system. In particular, at very high shear only a single mode with $k_\phi \rho_i \simeq 0.5$ is excited in the region of the maximum density gradient; (2) The frequency spectrum obtained by the probe (which has no $\vec{k}$-resolution) is very similar to that obtained by microwave scattering at a scattering angle $\theta_\phi \approx 60°$ corresponding to $k_\phi \rho_i \simeq 0.5$; (3) These fluctuations are due to drift waves since the observed frequency of 20 kHz is in reasonable agreement with the calculated value of 25 kHz from the drift wave dispersion formula of Eq. (6) (for $k_\phi \rho_i \approx 0.5$ and a density gradient scale length $a \approx 7$ cm). Further, earlier probe studies reported in Refs. [3,4] also showed that these are drift wave fluctuations.

In order to demonstrate the shear stabilization of the drift waves we reduced the value of the magnetic shear strength to an intermediate value corresponding to an $\langle L_s \rangle \approx 5.0$ m with $I_T/I_P \approx 0.2$. The observed fluctuation spectrum in this intermediate shear condition is shown in Fig. 3. Here again this data was taken in a helium plasma at a filling pressure of 1.5×10^{-6} Torr. It is seen from Figs. 2 and 3 that the frequency spectrum of the fluctuations in the intermediate shear condition is much broader than that in the high magnetic shear condition. Since the half width $\Delta\omega/\omega$ is a measure of the normalized growth rate γ/ω of the drift waves, it is clear that increase in the value of the magnetic shear tends to stabilize the drift wave fluctuations under study. In Fig. 3 we show the fluctuation spectrum obtained by microwave scattering for scattering angles $\theta_\phi \approx 75°$ (corresponding to $k_\phi \rho_i \approx 0.25$), $\theta_\phi \approx 60°$ (corresponding to $k_\phi \rho_i \approx 0.5$), and $\theta_\phi \approx 45°$ (corresponding to $k_\phi \rho_i \approx 0.71$). The spectrum obtained by microwave scattering at a scattering angle $\theta_\psi \approx 30°$ corresponding to $k_\psi \rho_i \approx 0.87$ is similar to that obtained at a scattering angle $\theta_\phi \approx 60°$ corresponding to $k_\psi \rho_i \approx 0.5$. Further, it was found that a significant amount of microwave scattering by the low-frequency fluctuations occurred also for a scattering angle $\theta_\chi \approx 15°$ corresponding to $k_\chi \rho_i \approx 0.97$. Thus, in the intermediate shear condition the excited drift waves had finite components of their wave vector $\vec{k}$ in all three directions (i.e., ϕ, ψ, and χ-directions). Further, in this intermediate shear condition very low frequency ($\omega << \omega_*$) fluctuations with a power spectrum peaked around $\omega \approx 0$ were also observed. This is in sharp contrast to the very high shear condition where a single mode with $k_\phi \rho_i \approx 0.5$ and $k_\psi \approx k_\chi \approx 0$ was excited. This seems to indicate that the system is trying to go towards a state of isotropic turbulence with decreasing values of the magnetic shear strength. As seen from Fig. 3, in this intermediate shear condition the normalized half width $\Delta\omega/\omega$ is about unity for all scattering angles. This implies that the growth rate γ of the drift waves under study is already about equal to the wave frequency ω. Since $\gamma \approx \omega$, it is not unreasonable to find some tendency towards a k-space isotropy in the observed fluctuation spectrum. Also it is seen from Fig. 3 that the peak frequency shifted from about 60 kHz for a scattering angle $\theta_\phi \approx 60°$ corresponding to $k_\phi \rho_i \approx 0.5$ to about 90 kHz for a scattering angle $\theta_\phi \approx 45°$ corresponding to $k_\phi \rho_i \approx 0.71$. These peak frequencies are in reasonably good agreement with the corresponding values (of about 50 kHz for $k_\phi \rho_i \approx 0.5$ and about 75 kHz for $k_\phi \rho_i \approx 0.71$) obtained from the theoretical drift wave dispersion relation of Eq. (6). The fact that these frequencies are somewhat higher than those in the high magnetic shear configuration is mainly due to the change in the density gradient scale length when the shear value was varied. It should be noted from Fig. 3 that the spectrum obtained with the probe is very similar to that obtained by microwave scattering at a scattering angle $\theta_\phi \approx 75°$ corresponding to $k_\phi \rho_i \approx 0.25$. However, the probe measurements failed to detect the peaked frequency spectrum as observed by microwave scattering at scattering angles $\theta_\phi \approx 60°$ corresponding to $k_\phi \rho_i \approx 0.5$ and

$\theta_\phi \simeq 45°$ corresponding to $k_\phi \rho_i \approx 0.71$. This is because the probes can only measure an integrated k-spectrum and in particular the probes have no k-resolution. Further, this result seems to indicate that the probe is more sensitive to longer wavelengths (i.e., $k_\perp \rho_i \lesssim 0.3$) and is very less sensitive to shorter wavelengths (i.e., $k_\perp \rho_i \gtrsim 0.3$) even though the exposed size Δr_p of the probe tip is sufficiently small compared to the wavelengths of the fluctuations under study [i.e., for our experiments $(\Delta r_p/\lambda_\perp) << 1/30$].

In Fig. 4 we show the fluctuation spectrum obtained by microwave scattering in a hydrogen plasma at a filling pressure of 5×10^{-6} Torr. The spectra obtained at scattering angles $\theta_\phi \approx 75°$ corresponding to $k_\phi \rho_i \approx 0.13$, $\theta_\phi \approx 60°$ corresponding to $k_\phi \rho_i \approx 0.25$, and $\theta_\phi \simeq 45°$ corresponding to $k_\phi \rho_i \simeq 0.36$ are shown in this figure. The observed shift of the peak of the spectrum from 20 kHz at a scattering angle $\theta_\phi \simeq 75°$ corresponding to $k_\phi \rho_i \approx 0.13$ to 60 kHz at a scattering angle $\theta_\phi \simeq 60°$ corresponding to $k_\phi \rho_i \simeq 0.25$ is consistent with the corresponding values of 25 kHz and 50 kHz respectively as predicted by the theoretical drift wave dispersion relation of Eq. (6). It should be noted that the data shown in this figure was taken with the maximum shear configuration corresponding to an average shear length $\langle L_s \rangle \approx 50$ cm with $I_T/I_P \simeq 1$. Even in this maximum shear configuration the spectrum in the hydrogen plasma did not show the highly localized single mode type spectrum as was the case in the helium plasma (see Fig. 2). Thus, from a comparison of the helium spectrum of Fig. 2 with the corresponding hydrogen spectrum of

Fig. 4 under the same maximum shear condition, it is clear that the smaller the ion mass is, the harder it is to stabilize the drift waves with magnetic shear. This is consistent with the prediction of the theoretical shear stability criterion of Eq. (8). Hence the helium data of Fig. 2 in conjunction with the corresponding hydrogen data of Fig. 4 provide a semiquantitative experimental demonstration of the ion mass dependence of the shear stability criterion for drift waves [see Eq. (8)].

When the value of the shear strength was further reduced, the plasma went into a state of strong turbulence with respect to the drift wave fluctuations. That is, with extremely low shear strength (i.e., $\langle L_s \rangle \gtrsim 5$ m with $I_T/I_P < 0.2$), the frequency power spectrum of the drift wave fluctuations as obtained by microwave scattering did not show the peak at the frequency expected from the linear dispersion relation of Eq. (6) (for any scattering angle). Indeed, the experimentally observed fluctuation spectrum was essentially the same (both in magnitude and shape) for all values of $k_\perp \rho_i$. This is illustrated in Fig. 5. The data shown in this figure were taken in an argon plasma at a filling pressure of 1.5×10^{-6} Torr. Here we have shown the spectrum as obtained by microwave scattering at scattering angles $\theta_\phi \approx 75°$ corresponding to $k_\phi \rho_i \simeq 0.75$, $\theta_\phi \simeq 60°$ corresponding to $k_\phi \rho_i \approx 1.50$, and $\theta_\phi \approx 45°$ corresponding to $k_\phi \rho_i \approx 2.1$. Although not shown in this figure, it was found that the spectra at scattering angles $\theta_\psi \approx 30°$ corresponding to $k_\psi \rho_i \approx 2.6$ and $\theta_\chi \approx 15°$ corresponding to $k_\chi \rho_i \simeq 2.9$ were very similar (both in magnitude and shape) to the ones shown in Fig. 5. This seems to indicate that the observed drift wave turbulence is fairly isotropic in k-space. In this figure the verticle scale is a logarithmic scale. The turbulent density fluctuations showed a strong dependence on frequency but no dependence on wave number (somewhat in sharp contrast to theoretical expectations). Indeed as also shown in this figure the power law dependence of the turbulent density fluctuations is of the form $(\delta n/n)_\omega^2 \propto \omega^{-6}$ for any scattering angle (i.e., for any value of $k_\perp \rho_i$) and for frequencies higher than about 20 kHz. But for frequencies less than about 20 kHz the fluctuation amplitude reached a saturated value of about 1% [i.e., $(\delta n/n)_\omega^2 \approx 10^{-4}$]. In Section 5 we will make a comparison of this observed turbulent spectrum with the corresponding predictions of the existing turbulent theories.

The experimentally observed ion mass dependence of the shear strengths which were needed to stabilize the drift waves under study are summarized in Fig. 6. In this figure we have divided the entire parameter space into three distinct regimes labelled A, B, and C. In regime A the observed fluctuation spectrum is highly localized around the region of the maximum density gradient, and the frequency power spectrum of the observed fluctuations is sharply peaked at a frequency corresponding to only one value of $k_\phi \rho_i$. That is, in regime A the observed fluctuation spectrum is of the single mode type and is similar to the one shown in Fig. 2. The observed frequency power spectrum of the fluctuations in regime B is a broad spectrum with a normalized half width $\Delta\omega/\omega$ of the order of unity, and for different scattering angles the frequency corresponding to the peak of the spectrum shifted according to the linear drift wave dispersion relation of Eq. (6). In other words the observed fluctuation spectrum in regime B is similar to the ones shown in Figs. 3 and 4. The curve labelled I shows the experimentally measured boundary for the transition from the high shear regime A [where $\Delta\omega/\omega < 1$] to the intermediate shear regime B [where $\Delta\omega/\omega$ is of order unity]. In regime C, the plasma is in a state of strong isotropic trubulence with respect to the drift wave fluctutions, and the power law dependence of the observed turbulent density fluctuations is of the form $(\delta n/n)^2_\omega \propto \omega^{-6}$ for any scattering angle (i.e., for any value of $k_\perp \rho_i$). That is, in regime C the observed fluctuation spectrum is of the type shown in Fig. 5. The curve labelled II shows the experimentally measured boundary for the transition from the intermediate shear regime B (where the spectra is of the type shown in Figs. 3 and 4) to the extremely low shear regime C (where the spectra is of the strong turbulence type similar to the one shown in Fig. 5). We should point out that our microwave scattering measurements of the fluctuation spectra were only carried out at discrete values of the scattering angles corresponding to discrete values of k. Consequently, our experimental measurements of the boundary curves I and II are not very precise. Nevertheless, the experimentally measured magnetic shear values corresponding to the boundaries between regimes A and B, and regimes B and C clearly showed a monotonical decrease with the increase in ion mass. To our knowledge this is the first experimental demonstration of the ion mass dependence of the magnetic shear marginal stability condition for drift waves.

In particular it is clear that larger is the ion mass, the easier it is to stabilize the drift waves with magnetic shear. It is seen from Fig. 6 that around very low values of ion mass, the experimentally measured marginal stability condition has a stronger ion mass dependence than that expected from the theoretical predictions of Eq. (8). However, for higher values of ion mass there is reasonably good agreement between our experimental results and the theoretical predictions of Eq. (8). In particular, our experimental results seem to indicate that the ion mass dependence of the magnetic shear marginal stability condition is more or less given by $(a/L_s) \propto (m_e/m_i)^{1/3}$. Further, since the constant of proportionality of the order of unity reasonably describes our experimentally observed marginal stability condition at higher values of ion mass, we conclude that our experimental results are reasonably consistent with the predictions [see Eq. (8)] of the available theories of stabilization of drift waves by magnetic shear [20, 21].

In microwave dc discharge plasmas strong drift wave turbulence was produced by reducing the value of the magnetic shear strength to extremely low values. However, it was found that strong turbulence could also be produced even in a high magnetic shear configuration by increasing the electron temperature T_e with a different auxiliary plasma heating scheme such as the neutral beam injection heating and Ohmic heating. The time behavior of the plasma parameters such as n and T_e and the low-frequency drift wave fluctuation amplitudes when a pulsed (10 msec) neutral hydrogen beam of about 75 kW at 15 kV was injected into a dc microwave target hydrogen plasma are shown in Fig. 7. The frequency power spectrum obtained at two different times ($t \approx 2$ msec and $t \approx 5$ msec) during the neutral beam pulse is summarized in Fig. 8. At $t \approx 2$ msec the electron temperature reached a value of about 40 to 50 eV and the density fluctuations were excited with a relatively large $[(\delta n/n)_\omega^2 \approx 5 \times 10^{-5}]$ but reasonably constant amplitude up to 20 to 30 kHz. As seen from Fig. 8, at $t \approx 2$ msec and for frequencies larger than about 30 kHz the fluctuation amplitude decreased monotonically with increase in frequency according to the relation $(\delta n/n)_\omega^2 \propto \omega^{-4}$. After 2 msec the electron temperature dropped to about 10 eV and the fluctuation level stayed relatively constant for the rest of the duration of the neutral beam pulse. The measured frequency power spectrum of the fluctuations at $t \approx 5$ msec is also shown in Fig. 8. As seen from this figure at $t \approx 5$ msec the fluctuation amplitude remained relatively constant up to about 100 kHz and thereafter decreased monotonically with increase in frequency according to the relation $(\delta n/n)_\omega^2 \propto \omega^{-4}$. In Fig. 8 we have also shown the turbulent spectrum obtained in an Ohmically heated plasma of $T_e \approx 30$ eV and $n \approx 3 \times 10^{12}$ cm^{-3}. Here again at low frequencies (i.e., less than about 500 kHz) the turbulent fluctuation spectrum tends to saturate at a value of $(\delta n/n)_\omega^2 \approx 3 \times 10^{-5}$, and at higher frequencies the spectrum showed a power law dependence of the form $(\delta n/n)_\omega^2 \propto \omega^{-(4-5)}$. We should point out that regardless of the nature of the plasma heating scheme (i.e., microwave dc discharge, neutral beam heating, or Ohmic heating), when the system was in the state of strong turbulence the turbulent density fluctuations showed a strong dependence on frequency [i.e., $(\delta n/n)^2_\omega \propto \omega^{-(4-6)}$] but showed no significant dependence on wave number. This seems to indicate that the linear drift wave dispersion relation of Eq. (6) is no longer valid in the fully developed strong turbulent state. In the literature Tsytovich [22] has shown that the turbulent dispersion is markedly different from the linear dispersion for the case of ion acoustic wave turbulence. However, we are not aware of any theoretical calculations of turbulent drift wave dispersion relation.

Another interesting result indicated by Fig. 8 is the fluctuation saturation level. Although the apparent saturated level at low frequencies $(\delta n/n)^2_\omega$ differs for the different plasma heating schemes or shear strength, the integrated fluctuation level $(\delta n/n)^2_o$ [see Eq. (2)] gives consistently $(\delta n/n)_o \simeq 3\%$ independently from the plasma conditions. Hence, we estimate that in the strong turbulent regime, the total density fluctuations $(\delta n/n) \simeq 5\ (\delta n/n)_o$ is about 15% [see disscussions following Eq. (2)].

4. SOME DISCUSSIONS

We now wish to make some remarks first about the strong turbulent state, and second about the possible dependence of the anomalous particle and energy confinement properties of plasmas on the level of drift wave fluctuations.

It is seen from Fig. 8 that regardless of the nature of the plasma heating scheme (i.e., microwave dc discharge, neutral beam heating, or Ohmic heating), when the system was in the state of strong turbulence the frequency power spectrum of the turbulent density fluctuations had a common behavior. At the low frequency side the turbulent density fluctuations tends to saturate at some constant value, and at the higher frequencies a power law dependence of the form $(\delta n/n)_\omega^2 \propto \omega^{-m}$ where $4 \lesssim m \lesssim 6$ was observed. In the early literature [23-25] several authors have reported on the observation of a similar drift-wave turbulent spectrum in entirely different plasma devices (such as in stellerators and in linear plasma devices). All of those earlier measurements of the turbulent spectrum were carried out with probes and it is generally known that probes do not have any k-resolution. However, here we have presented the observation of a similar turbulent spectrum by microwave scattering at different scattering angles corresponding to different values of $\vec{k}$. The puzzling feature of our measurements is that the observed turbulent density fluctuations showed the strong dependence [of the form $(\delta n/n)_\omega^2 \propto \omega^{-m}$ where $4 \lesssim m \lesssim 6$] on frequency at the higher frequencies but showed no corresponding significant dependence on wave number (and in fact within our experimental accuracy there was no dependence at all on the wave number for $0.2 \lesssim k_{\perp}\rho_i \lesssim 4$).

The universality of the spectrum under such diverse conditions suggests that the final turbulent state is more or less independent of the excitation mechanism. This type of a universal behavior has been known in ordinary hydrodynamic turbulence. In the study of turbulence in incompressible fluids one finds that there exists an inertial range in k-space where the k-spectrum is universal and it was found by Kolmogorov [26] by dimensional analysis that the spectrum should vary as $k^{-5/3}$. In the turbulent stationary state there exists a nonlinearly coupled statistical distribution of eddies of various spatial dimensions. The largest size (i.e., the shortest k) of the eddies is determined by the physical size of the system (i.e., the boundary conditions), and the smallest size (i.e., the largest k) is determined by the efficiency of viscous damping. In essence the k-Fourier spectrum of this statistical distribution of the number of eddies of different sizes yield the familiar Kolmogorov k-spectrum of the hydrodynamic turbulent stationary state. If we now take the similar view for drift-wave turbulence as was done by Chen [23], then one can easily show that the spectra of the potential fluctuations $\delta\phi$ associated with the drift wave density fluctuations δn should show a power law dependence of the form $(\delta\phi)^2 \propto k^{-5}$. If further we assume that a small but finite $k_{\parallel}$ always exists in a turbulent state so that electrons flowing along $\vec{B}$ preserved the approximate relation $n \approx n_o \exp(-e\delta\phi/\kappa T_e)$, then one can easily show that the density fluctuations in the stationary turbulent state should obey a power law dependence of the form [23]

$$(\delta n/n)_k^2 \propto k^{-5} . \qquad (9)$$

Furthermore, if we now assume that for drift waves the turbulent dispersion is essentially the same as the linear dispersion (somewhat in sharp contrast to the recent theories of ion acoustic wave turbulence by Tsytovich [22]), then it is relatively easy to show from Eq. (9) that in the turbulent stationary state

$$(\delta n/n)_\omega^2 \propto \omega^{-5} , \qquad (10)$$

for drift waves of $k_\perp \rho_i < 1$.

Our microwave scattering experiment and the probe measurements reported in the early literature [23-25] do indicate that at higher frequencies the observed turbulent density fluctuations follow a power law dependence of the form given by Eq. (10). However, since the probes have no k-resolution it is fair to say that all of these experiments and ours in particular indicate that the power law dependence of the form given by Eq. (9) is in no way close to reality. We therefore conclude that our experimental results (and possibly also the earlier results obtained with probes) are in complete disagreement with the existing theory [23] of drift wave strong turbulence. Nevertheless, the fact that our experimental results show good agreement with Eq. (10) but show complete disagreement with Eq. (9) is an important piece of experimental information that one should bear in mind if one wishes to formulate a truly satisfactory theory of strong drift wave turbulence. Furthermore, since the observed frequency power spectrum is not of a Lorentzian type, it is hard to reconcile our experimental results on the basis of turbulent line broadening [22].

In plasma physics it is known that in general there are two types of plasma wave instabilities, namely convective and absolute. These two distinct types of instabilities may eventually evolve into two distinct types of strong turbulent states. If we conjecture that in one of these turbulent states the system consists of nonlinearly coupled statistical distribution of eddies of roughly a uniform distribution in size but having different energy content, then by the uncertainty principle eddies of different energies will last for different times. The Fourier transform of such an ensemble can in principle yield a power law dependence on frequency without showing any significant dependence on wave number (a feature that is qualitatively consistent with our experimental results). However, at present a mathematical formulation based on such a conjecture does not seem to exist in the literature.

We remarked earlier that in the FM-1 spherator, the previously observed [3, 4] empirical relationship between the shear strength and the anomalous transport coefficient is given by Eq. (4). For the sake of completeness we now wish to make some comments: First, on the relationship between our measured level of drift wave turbulence and the value of the anomalous diffusion coefficient as given by Eq. (4); and second, on the nonlinear saturation level of drift wave fluctuations in the strongly turbulent stage. The anomalous particle flux Γ due to the electrostatic drift wave fluctuations may be written

$$\Gamma = - D\nabla n = \langle \delta n \times \delta E \rangle / B \,, \tag{11}$$

where δn is the density fluctuations due to drift waves, δE is the associated electric field fluctuations, and the angular bracket refers to an ensemble average. Since $\delta E = -k_\phi \delta\Phi$, $\delta n/n = e\delta\Phi/\kappa T_e$ and $\nabla n/n = - n/a$, the anomalous diffusion coefficient D of Eq. (11) may be written as

$$D \approx \left(\frac{\delta n}{n}\right)_o^2 (k_\phi\, a\kappa T_e/eB)\sin\alpha \,, \tag{12}$$

where α is the phase angle between the density fluctuations δn and the associated potential fluctuations $\delta\Phi$. By comparing the empirical relation of Eq. (4) with the phenomenological relation of Eq. (12), we get

$$\sin\alpha = (L_s/a)(k_\phi a)^{-1}(\delta n/n)_o^{-2}(C/16)\,. \tag{13}$$

As discussed in Ref. [27] it should be noted that in weak turbulence when $\gamma < \omega$, the sine of the phase angle between the density and potential fluctuations should be approximately equal to the normalized growth rate γ/ω. Further, since in weak turbulence the normalized half width $(\Delta\omega/\omega)$ of the fluctuation spectrum is also approximately equal to the normalized growth rate γ/ω, it is seen from Eq. (13) that

$$(\Delta\omega/\omega) \approx (L_s/a)(k_\phi a)^{-1}(\delta n/n)_o^{-2}(C/16). \qquad (14)$$

Our experimental measurements did show that the observed values of $(\Delta\omega/\omega)$ increased with increasing values of the shear length L_s. However, we have not carried out a detail experimental study of the exact functional dependence of $(\Delta\omega/\omega)$ on (L_s/a) in the weak turbulent regime. Nevertheless, it is instructive to point out that for the helium data of Fig. 2, Eq. (14) predicts a value of $\Delta\omega/\omega$ of about 0.02 while the experimental value of $\Delta\omega/\omega$ is about 0.25. It does therefore appear that in the weak turbulent regime, our present experimental results in conjunction with the previously reported [3, 4] empirical relation of Eq. (4) seem to indicate that the observed $(\Delta\omega/\omega)$ is about ten times the value of sin α of Eq. (13), while theoretically [27] one expects that $(\Delta\omega/\omega) \approx (\gamma/\omega) \approx \sin\alpha$. We do not know the physical reason for this discrepancy between theory and experiment.

The other comment we wish to make is related to the saturation level of the fluctuation amplitude in the strongly turbulent regime. As shown in Fig. 8, in the strong turbulent regime the fluctuation amplitude tends to saturate at $(\delta n/n)_o \simeq 3\%$ regardless of heating scheme, shear strength or electron temperature [see Eq. (2)]. According to Kadomtsev [17], when strong turbulence develops, the growth rate γ reaches ω and the oscillation amplitude increases to such an extent that the perturbation of density gradient $k_\psi \delta n$ becomes of the order of the mean gradient $\nabla n \simeq n/a$. That is, for strong turbulence

$$\left(\frac{\delta n}{n}\right)_o^2 \simeq (k_\psi a)^{-2} . \tag{15}$$

In Eq. (15) k_ψ can be replaced by k_ϕ, since in the strong turbulent regime our experimental measurements seem to indicate that $k_\psi \approx k_\phi$. For the experimental conditions of Fig. 8, the theoretical Eq. (15) predicts that $(\delta n/n)_o$ should saturate at a value of about 2 to 3%, while the experimentally observed saturation value of $(\delta n/n)_o$ is about 3%. Thus, in the strong turbulent regime, our experimentally measured level of drift wave turbulence appears to be in reasonable agreement with that predicted theoretically by Kadomtsev [see Eq. (15)]. However, in strong turbulence our experiment indicates that the observed k-spectrum of the turbulent density fluctuations is fairly isotropic in $k_\perp$-space with a width $\Delta k_\perp$ of the order of $k_\perp$. Consequently, we estimate that the total (i.e., after a k-space integral) fluctuation level $(\delta n/n)$ is about 15% [see discussions following Eq. (2)]. Thus the observed total fluctuation level is somewhat higher than Kadomstsev's estimate [17].

Finally we wish to draw the readers attention to the very low frequency (i.e., $\omega << \omega_*$) fluctuations with a power spectrum peaked around $\omega \approx 0$ in Figs. 3 and 4. As seen from Fig. 2(a), these very low frequency fluctuations around $\omega \approx 0$ are absent in the very high magnetic shear condition where only a single mode type drift wave spectrum with $k_\phi \rho_i \approx 0.5$ was seen. In other words these very low frequency fluctuations are absent in regime A of Fig. 6 and they appear only when the toroidal plasma is in regime B of Fig. 6 (i.e., when the shear strength is such that the drift wave of $\omega \simeq \omega_*$ is in the weak turbulent regime). In regime B the frequency power spectrum of these very low frequency fluctuations is peaked around $\omega \approx 0$. As the shear strength is further reduced these very low frequency ($\omega << \omega_*$) fluctuations grew at a relatively faster rate than the high frequency ($\omega \simeq \omega_*$) drift wave fluctuations. In regime C of Fig. 6, these very low frequency fluctuations have already reached their nonlinear saturated stage and their frequency power spectrum is flat (see Fig. 5). It may be pointed out that other recent microwave and CO_2 laser scattering experiments on the adiabatic toroidal compressor (ATC) plasmas [28] also revealed a fluctuation spectrum of the weak turbulence type similar to the ones shown in Figs. 3 and 4. This experimental observation of the very low frequency ($\omega << \omega_*$) fluctuations then raises the following two theoretical questions: First, what are these very low frequency fluctuations? Are these a linear mode of a toroidal plasma with magnetic shear, or are these some nonlinear modes due to the presence of drift wave turbulence in the plasma? Second, what is the source of free energy that drives these very low frequency modes unstable? From linear dispersion theory the two possible very low frequency modes are the convective cells [29] and ion acoustic waves with negative parallel phase velocity [17]. According to the recent drift wave turbulence theory of Dupree [30], he finds that at very low frequencies one can have turbulent ballistic modes (i.e., clumps in phase space). All three of these modes (i.e., convective cells, ion acoustic waves, and clumps) should have very long parallel (i.e., parallel to $\vec{B}$) wavelengths (i.e., very small $k_\parallel$) and can be parametrically excited by the turbulent high frequency (i.e., $\omega \approx \omega_*$) drift waves. Due to our experimental limitations we are not in a position to state that our experimentally observed very low frequency fluctuations in Figs. 3 and 4 are convective cells or ion acoustic waves or clumps. All these three types of modes are likely candidates for the experimental conditions of Figs. 3 and 4.

5. SUMMARY AND CONCLUSIONS

The principal results of our experimental measurements can be summarized as follows: (1) In microwave dc discharge plasmas the measured dispersion relation of the observed fluctuations by microwave scattering was in reasonably good agreement with that predicted from the theoretical linear drift wave dispersion relation of Eq. (4) when the magnetic shear strength is sufficiently large. In high magnetic shear configuration the observed frequency power spectrum of the fluctuations was of a single mode type with a half width $(\Delta\omega/\omega) \simeq 1/4$ and had a single value of $k_\phi \rho_i$ which is less than unity with $k_\psi \simeq k_\chi \simeq 0$. As the shear strength was reduced the half width $(\Delta\omega/\omega)$ increased, thus showing the effect of shear stabilization of drift waves. In the intermediate shear configuration the half width $(\Delta\omega/\omega)$ was of order unity and the observed fluctuations had finite components of $\vec{k}$ in all the three directions (i.e., ϕ, ψ, and χ-directions). However, even when $(\Delta\omega/\omega)$ was of order unity these fluctuations obeyed the linear drift wave dispersion relation of Eq. (4). Furthermore, in this weak turbulent regime for drift waves of $\omega \simeq \omega_*$, very low frequency $(\omega << \omega_*)$ fluctuations with a frequency power spectrum peaked around $\omega \approx 0$ were also observed. These $\omega << \omega_*$ fluctuations may be convective cells, ion acoustic waves or turbulent ballistic modes (i.e., clumps) and are driven unstable by parametric coupling to the turbulent drift waves of $\omega \lesssim \omega_*$. As the shear strength was further reduced the system went into a state of strong turbulence with respect to drift waves. The turbulent density fluctuations showed a strong dependence [of the form $(\delta n/n)^2_\omega \propto \omega^{-6}$] on frequency but no dependence on wave number (somewhat in sharp contrast to theoretical expectations). The passage of the system into the strong turbulent state occurred rather abruptly with a relatively small reduction in shear strength. (2) The experimentally measured ion mass dependence of the magnetic shear marginal stability condition was in reasonably good agreement with the theoretical prediction of Eq. (8). (3) Our results seem to indicate that the response of a probe is a very sensitive function of the wave length even when the probe tip is sufficiently small compared to the wave lengths of the fluctuations under study. In particular the power spectrum obtained with probes may be somewhat misleading since probes have a tendency to respond only to very long wave length fluctuations. (4) It was found that the strong turbulent state can also be produced even in a high magnetic shear configuration by increasing the electron temperature T_e with a different auxiliary plasma heating scheme such as the neutral beam injection heating and Ohmic heating. At the low frequency side the turbulent density fluctuations tend to saturate around some constant value, and at the higher frequencies a power law dependence of the form $(\delta n/n)_{\omega}^2 \propto \omega^{-m}$ where $4 \lesssim m \lesssim 6$ was observed.

In conclusion we wish to point out that our present experimental study yields the following physical information about drift waves in a toroidal plasma: (1) It is interesting and somewhat instructive to find that the linear drift wave dispersion relation is obeyed not only when $\gamma << \omega$, but also in the weak turbulent regime where $\gamma \lesssim \omega$. (2) The experimentally measured ion mass dependence of the magnetic shear marginal stability condition is in reasonable agreement with the theoretical expectations. To our knowledge, this is the first experimental demonstration of the marginal stability criterion. (3) In the weak turbulent regime when $\gamma < \omega$, our results seem to indicate that the observed $(\Delta\omega/\omega) \approx 10 \sin\alpha$, while theoretically one expects that $(\Delta\omega/\omega) \approx (\gamma/\omega) \approx \sin\alpha$. At present we do not know the physical reason for this discrepancy between theory and experiment. (4) In the strong turbulent regime (when γ is of the order of ω) the measured level of drift wave turbulence is in reasonable (i.e., within an order of magnitude) agreement with that predicted theoretically by Kadomtsev. (5) Finally, the puzzling feature of our measurements is that in strong turbulence the observed turbulent density fluctuations showed a strong dependence [of the form $(\delta n/n)^2_\omega \propto \omega^{-m}$ where $4 \lesssim m \lesssim 6$] on frequency, but showed no corresponding significant dependence on wave number. In other words, our experimental results in the strong turbulent regime are in complete disagreement with Chen's theory of drift wave strong turbulence. We believe that this is an important piece of experimental information that one should bear in mind if one wishes to formulate a truly satisfactory theory of strong drift wave turbulence.

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REFERENCES

[1] SINNIS, J., OKABAYASHI, M., SCHMIDT, J., YOSHIKAWA, S., Phys. Rev. Lett. 29 (1972) 1214.

[2] OKABAYASHI, M., FREEMAN, R., Phys. Fluids 15 (1972) 359.

[3] EJIMA, S., OKABAYASHI, M., Phys. Fluids 18 (1975) 904.

[4] ANDO, K., et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 5th Int. Conf. Tokyo, 1974) 2, IAEA, Vienna (1975) 103.

[5] FREEMAN, R., et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. Conf. Madison, 1971) 1, IAEA, Vienna (1971) 27.

[6] OKABAYASHI, M., et al., in Controlled Fusion and Plasma Physics (Proc. Conf. Grenoble, 1972) 1, Centre d'Estudes Necléaires de Grenoble (1971) 92.

[7] MEADE, D., et al., in Toroidal Plasma Confinement (Proc. 3rd Int. Symp. Garching, 1973) C8.

[8] PACHER, P. H., VON GOELER, S., Phys. Fluids 14 (1971) 1260.

[9] VON GOELER, S., SADOWSKI, M., PACHER, H., YOSHIKAWA, S., Phys. Fluids 13 (1970) 790.

[10] SAUTHOFF, N., Ph.D. Dissertation, Princeton University (1975).

[11] ARUNASALAM, V., OKABAYASHI, M., HAWRYLUK, R., SUCKEWER, S., Phys. Rev. Lett. 36 (1970) 726.

[12] ARUNASALAM, V., OKABAYASHI, M., HAWRYLUK, R., SUCKEWER, S., Phys. Fluids, (to be published).

[13] BEKEFI, G., Radiation Processes In Plasmas (John Wiley and Sons, Inc.,New York, 1966), Chap. 8.

[14] Sheffield, J., Plasma Scattering of Electromagnetic Radiation (Academic Press, New York, 1975).

[15] ANDO, K., OKABAYASHI, M., SUCKEWER S., ARUNASALAM, V., HAWRYLUK, R., WILSON, J., Nucl. Fus. (to be published), and SUCKEWER, S., et al., Bull. Am. Phys. Soc. 20 (1975) 1306.

[16] DAVIS, S. L., et al., Princeton Plasma Physics Laboratory Report, PPPL-1289.

[17] KADOMTSEV, B., Plasma Turbulence, (Academic Press, New York, 1965), Chap. 4.

[18] KADOMTSEV, B., POGUTSE, O., Zh Eksp. Teor. Fiz. 51 (1966) 1934, [Sov. Phys. JETP 24, (1967) 1172].

[19] COPPI, B., LAVAL, G., PELLAT, R., ROSENBLUTH, M., Nucl. Fusion 6 (1966) 261.

[20] RUTHERFORD, P., FREEMAN, E., Phys. Fluids 10 (1967) 1007.

[21] PEARLSTEIN, L., BERK, H., Phys. Rev. Lett. 23 (1969) 220.

[22] TSYTOVICH, An Introduction to the Theory of Plasma Turbulence, (Pergamon, New York, 1972), Chap. 5.

[23] CHEN, F. F., Phys. Rev. Lett. 15 (1965) 381.

[24] HENDEL, H., CHU, T. K., Methods of Experimental Physics, 9A (Academic Press, New York, 1970) Chap. 9.

[25] BOL, K., Phys. Fluids 7 (1964) 1855.

[26] TOWNSEND, A. A., The Structure of Turbulent Shear Flow, (Cambridge University Press, England, 1956); BATCHELOR, G. K., The Theory of Homogeneous Turbulence, (Cambridge, University Press, England, 1956); CHANDRASEKHAR, S., J. Madras University, B27 (1957), 251.

[27] SAGDEEV, R. Z., GALEEV, A. A., Nonlinear Plasma Theory, (W. A. Benjamin, Inc., New York, 1969) Chap. 3.

[28] MAZZUCATO, E., Phys. Rev. Lett. 36 (1976) 792; GOLDSTON, R. J., MAZZUCATO, E., SLUSHER, R. E., SURKO, C. M., Princeton University Plasma Physics Laboratory Report PPPL-1290 (1976).

[29] OKUDA, H., DAWSON, J. M., Phys. Fluids 16 (1973) 408. In order to explain the experimental results reported in Ref. 28, a possible mode coupling between the very low frequency modes such as the convective cells and the high frequency drift waves (originating from the polarization $\vec{E} \times \vec{B}$ drift of the ions) has been recently examined by K. Mima and A. Hasegawa. HASEGAWA, A., Private Communication and also MIMA, K., HASEGAWA, A., Bull. Am. Phys. Soc. 21 (1976) 1180. HORTON, W., Phys. Rev. Lett. 37 (1976) 1269.

[30] DUPREE, T. H., Phys. Rev. Lett. 25 (1970) 789; DUPREE, T. H., the recent private communication and also Bull. Am. Phys. Soc. 21 (1976) 1115.

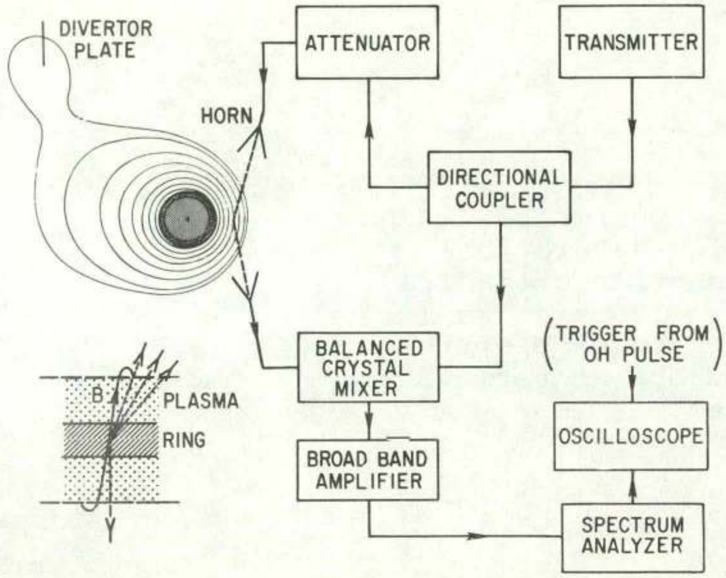

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Fig. 1. Schematic diagram of the experimental arrangement. Insert on the lower left hand corner shows the magnetic field configuration.

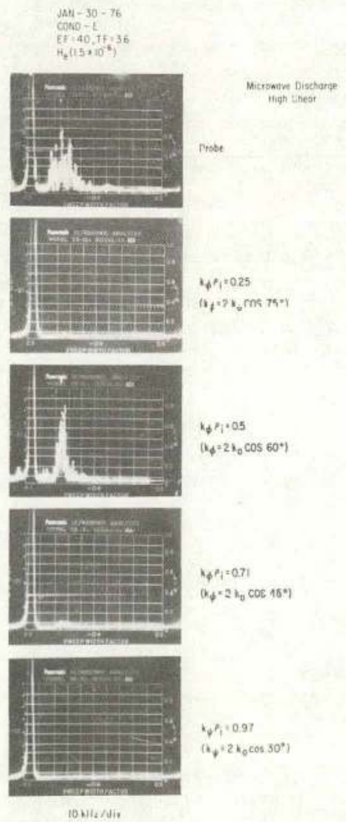

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Fig. 2(a). The observed frequency power spectrum by probe and by microwave scattering in high magnetic shear configuration in a helium plasma. The band width of the spectrum analyzer $\delta f \approx 2$ kHz.

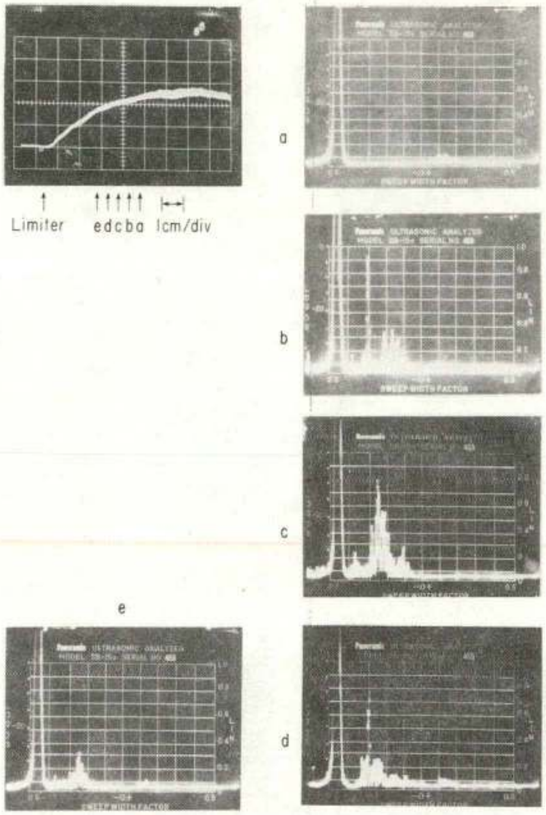

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Fig. 2(b). On top left hand corner is the ion saturation current as a function of radial position. Shown from (a) to (e) is the frequency power spectrum observed by a probe at various radial positions.

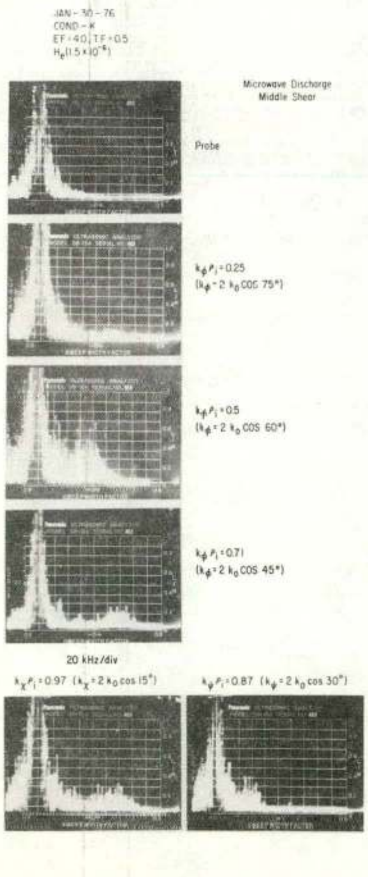

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Fig. 3. The frequency power spectrum observed by probe and by microwave scattering in the middle shear configuration in a helium plasma. Again $\delta f \simeq 2$ kHz.

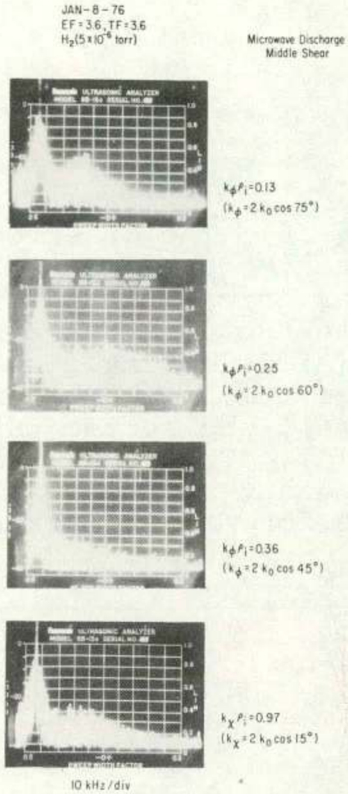

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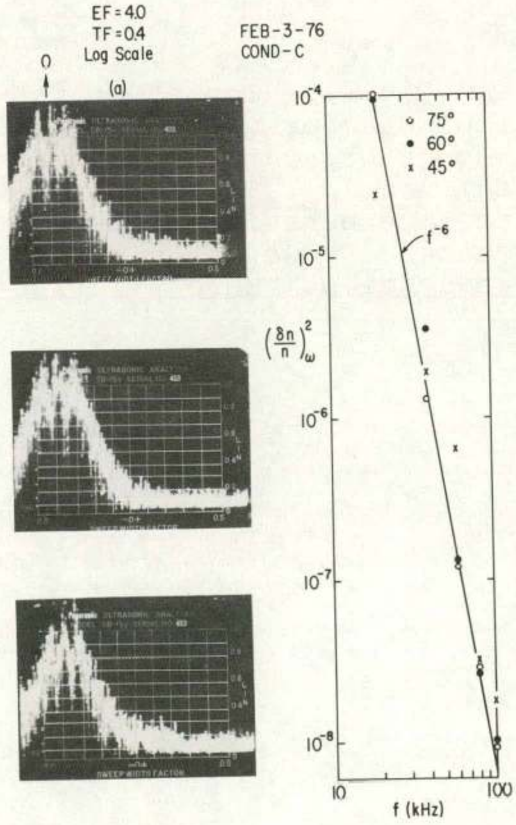
Fig. 4. The frequency power spectrum observed by microwave scattering in high shear configuration in a hydrogen plasma. $\delta f \approx 2$ kHz.

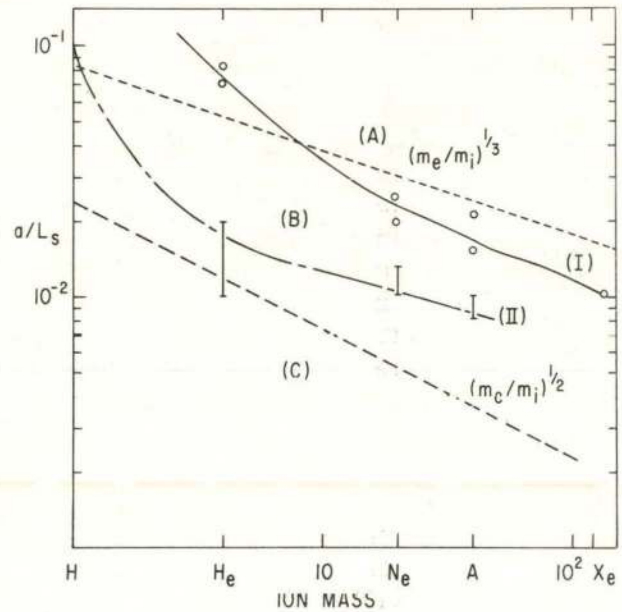


766151

Fig. 5. On left is the frequency power spectrum observed by microwave scattering in low shear configuration in an Argon plasma. On right we show the power law dependence of the observed fluctuation spectrum at high frequencies. $\delta f \approx 2$ kHz.

763997

Fig. 6. The observed ion mass dependence of the shear strengths which were needed to stabilize the drift waves. In regime (A) is a single mode-type spectrum, weak turbulence regime (B), and strong turbulence regime (C). The dashed lines are the different theoretical predictions for marginal stability



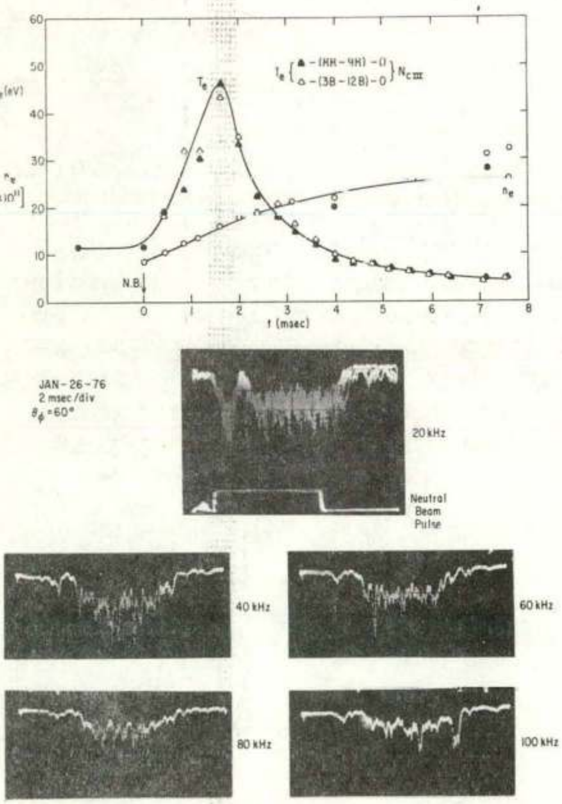


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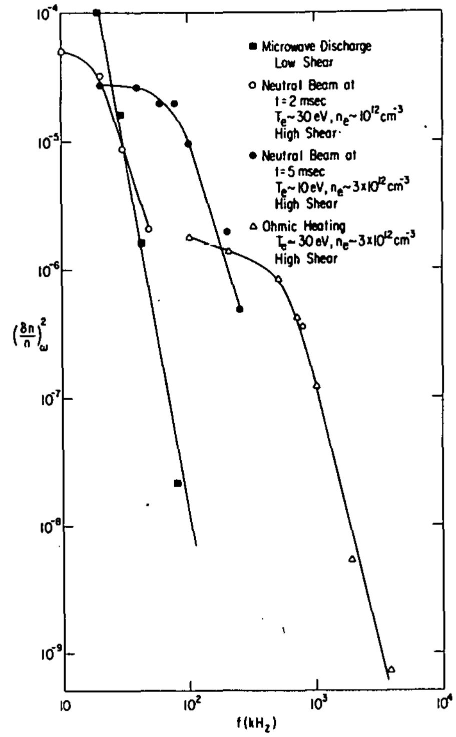
Fig. 7. Top shows the time behavior of density and temperature during the neutral beam heating. Bottom shows the time behavior of the scattered power at various frequencies. Here $\delta f \approx 10$ kHz.



766062

Fig. 8. A comparison of the turbulent spectrum obtained by microwave scattering in plasmas produced by three different heating schemes. Here all data were normalized to a receiver band width $\delta f \approx 2$ kHz.