INSTITUTE OF PLASMA PHYSICS

NAGOYA UNIVERSITY

RESEARCH REPORT

NAGOYA, JAPAN

The Shear Stabilization of
The Collisionless-Drift-Wave Instability

Y. Nishida*, T. Dodo+, T. Kuroda,
and G. Horikoshi#

IPPJ-166 June 1973

Further communication about this report is to be sent to the Research Information Center, Institute of Plasma Physics, Nagoya University, Nagoya, JAPAN

* Permanent Address: Department of Electrical Engineering, Utsunomiya University, Utsunomiya.

+ Central Research Laboratory, Hitachi Ltd. Kokubunji, Tokyo.

National Laboratory for High Energy Physics, Tsukuba, Ibaraki Pref.

Abstract

Stabilization of the drift wave instability by the magnetic shear is studied in a linear stellarator with $\ell = 3$ helical windings. The critical shear for stabilization strongly depends on the ion temperature, where ion temperature is controlled. Near stabilization, it is shown that the ion Landau damping becomes effective.

Stabilization of unstable electrostatic drift waves by the magnetic shear has been investigated both theoretically[1-4] and experimentally.[5-8] Rutherford and Frieman[1] have shown that the local wave packet of the drift wave ceases to grow if the characteristic length of the magnetic shear $L_s = [(r/L)d\iota/dr]^{-1}$ satisfies the condition: $R/L_s > (m/M)^{1/3}$, where ι is the rotational transform angle, R the density gradient scale length, m and M the electron and the ion mass, respectively. The parallel ion motion has not been taken into account in this critical value. If the ion contribution is taken into account, it always has a stabilizing effect, i.e., it leads to a smaller critical value of shear. Krall and Rosenbluth[2] have derived another criterion in the case of a local mode of drift wave instability. When magnetic shear is applied to plasma, the width of the effective potential well is expanded in the radial direction to the regions where the parallel ion Landau damping becomes effective. Their stability criterion is given by

$$\frac{R}{L_s} > \delta_{crit} = \frac{1}{4}\frac{\rho_i}{R}\left[\frac{T_i}{T_e}\left(1 + \frac{T_i}{T_e}\right)\right]^{-1}, \qquad (1)$$

where ρ_i is the ion Lamor radius, T_i and T_e the ion and the electron temperature, respectively.

Experiments performed hitherto[5-8] indicate that the fluctuations can be suppressed by the magnetic shear field, but there have been no quantitative investigations on the stabilization mechanism of the collisionless-drift-wave instability.

In the present experiment, the ion temperature is controlled and it is shown that the critical shear for stabilization depends on the ion temperature,[9] and is rather weaker than that predicted theoretically. Further, we show quantitatively that the stabilization by the magnetic shear comes from the parallel ion Landau damping.

The experiments are performed on the "QP-Machine" of Nagoya University.[10] The Helium Plasma produced by a PIG discharge is diffused into the experimental region, where the present experiments are performed, through a gas chamber which has a rather high gas pressure (order of 10^{-3} Torr). In this chamber only the ion temperature is controlled by ion-neutral collisions. The experimental region is bounded by two metallic orifices with holes of 2.0 cm diameter. The wall is metallic, and is 130 cm in length by 9.4 cm in diam.. Outside the metallic wall of the experimental region, ℓ, = 3 helical coils with a pitch L = 53 cm are wound, and the current in a coil I_H is varied up to 2900 A. The plasma density as measured by Langmuir probes is $(1.5 \sim 3.0) \times 10^9$ cm^{-3} and the electron temperature is about 4 eV in the column center. Ion temperatures are measured by an electrostatic analyser and the ion sensitive probe (I. S. P).[11] The instability signals are detected by Langmuir probes biased fully negative or at floating potentials. The detected siganals are analysed by a frequency spectrum analyser, a correlator, and an ac-voltmeter through a band=pass filter.

When the pressure P_G near the gas chamber[12] is changed, the ion temperature is changed, but the background neutral pressure in the experimental region does not change ($6.0 \times 10^{-6} \leq p \leq 7.3 \times 10^{-6}$ Torr). The dependence of temperature on P_G is shown in Fig.1. We can see in this figure that the ion temperature can be varied in the range of about 0.9 to 2 eV, while the electron temperature does not change within the experimental errors throughout the present experimental conditions.

The density fluctuations have a typical peak with frequency near 23 kHz in the uniform magnetic field $B_o = 600$ G at $r = 3$ cm where the density gradient is maximum (a typical density gradient scale length is 1.5 - 0.7 cm). In the present plasma, there is a radial electric field. The plasma rotation frequency f_E by that field is about $4 \sim 6$ kHz, while the drift frequency by the density gradient is $14 \sim 18$ kHz with the measured plasma parameters after the correction for finite ion Larmour radius. Thus, the wave of 23 kHz is identified as the unstable collisionless-drift wave after the correction of $\vec{E} \times \vec{B}$ plasma rotation. The drift wave has an $m = 1$ azimuthal mode, and the maximum amplitude n_1/n_o, which depends on the ion temperature, is in the range $0.15 \sim 0.2$ at $r = 3$ cm, where n_o is the steady state plasma density and n_1 the perturbed value. The parallel wave length is about twice the distance between the two orifices. The present drift wave does not propagate radially (non-convective mode).[13]

When the magnetic shear is applied, the drift waves can be diminished as shown in Figs.2 and 3. Figure 2 is obtained from the auto-correlation technique. We can see in this figure that the mode with $f = 23$ kHz is mainly stabilized but that the frequency shift scarcely occures. The regions where the wave exists, do not change appreciably with the magnetic shear in the radial direction. The wave amplitude changes as seen in Fig.3, when the ion temperature and also the shear strength are changed. When the ion temperature is rather high, the drift wave amplitude can be reduced to about 18 % of the amplitude without the shear, while under the lowest ion temperature, the wave can only be stabilized to 55 % of the initial value. It is also seen in Fig.3 that the wave amplitude decreases almost exponentially in the rather high R/L_s regions. The critical value δ_{crit} for stabilization is determined if the results are extrapolated to the zero amplitude. The critical values lie in the ranges of about 0.025 ($T_i = 2.0$ eV) to 0.08 ($T_i = 0.9$ eV), depending on the ion temperature.

The critical values given by Eq.(1) are $\delta_{crit} = 0.06$ ($T_i = 2.0$ eV) to 0.1 ($T_i = 1.0$ eV),[14] as the present typical values of ρ_i/R are $1.2 \sim 0.8$. The critical values determined experimentally are a little smaller than that obtained theoretically. In the theoretical work,[2] it has been assumed that the ion Landau damping is completely effective, i.e., $\omega/k_{\parallel}^{eff}v_i < 1$, when the wave is stabilized by the magnetic shear, where $k_{\parallel}^{eff}$ is the parallel wave number effected by the shear and is given by $k_{\perp}x/L_s$. In the present experiment, however, $\omega/k_{\parallel}^{eff}v_i$ is larger than one, as will be shown later, and the ion Landau damping effect would be weaker than that expected theoretically. So, the ion damping effect must be taken into account carefully.

The growth rate γ of the drift-wave instability is given as follows with the local approximation in the absence of the shear.

$$\frac{\gamma}{\omega^*} = \frac{2\pi}{k_z v_e} \frac{\beta(1-\beta)}{(2-\beta)^3} \omega^* - \frac{4\pi}{k_z v_i} \frac{\beta^2}{(2-\beta)^3} e^{-z^2} \cdot \omega^*, \quad (2)$$

where $\beta = I_o e^{-b}$, $b = k_{\perp}{}^2 T_i/M\omega_{ci}^2$, $z = \omega/k_z v_i$, ω^* is the drift angular frequency, and v_i and v_e are the ion and electron thermal velocity, respectively. Here, we used the approximation $z > 1$, tentatively. When the magnetic shear is applied, the growth rate cannot be obtained rigorously, and we assumed that $k_z = k_{\parallel o} + k_{\parallel}^{eff}$ as the shear is rather weak and should not change the system drastically, and $k_{\parallel o}$ is the parallel wave number without the shear and is determined by the length between the bounding orifices. Further, an ion viscosity damping is neglected, since it is about an order of magnitude smaller than the other terms. At first, we estimated the growth rate when the magnetic shear is absent. We confirmed that the ion damping term (the second term in the right hand side of Eq.(2)) is always smaller than the electron growth term (the first term in the right hand side), i.e. γ/ω^* must be about 6×10^{-2} to grow the drift wave sufficiently. Next, when the magnetic shear is applied, the wave growth term contributed by the resonance electrons becomes $(1.37 - 0.97) \times 10^{-7}\omega^*$ under the present experimental condition at the critical shear. The ion damping term is calculated as follows: When T_i is 2.0 eV, the wave damps away at about $\delta_{crit} \sim 0.025$, and there $\omega/k_{\parallel}^{eff}v_i$ is about 3.1 but $\omega/k_z v_i$ is about 1.25 and the ion damping term is $0.48 \times 10^{-5}\omega^*$ at the critical point. Here, we took x to be the wave spreading width and assumed that $x \simeq 1.0$ cm. When T_i is 0.9 eV, $\delta_{crit} \sim 0.08$, $\omega k/k_{\parallel}^{eff}v_i \sim 1.7$ and $\omega/k_z v_i \sim 1.0$. So, the ion damping term is $1.4 \times 10^{-5}\omega^*$. These values of $\omega/k_{\parallel}^{eff}v_i$ are still larger than one, but the values of $\omega/k_z v_i$ are nearly one and the growth term by electrons is smaller than the damping term by ions. The ambiguity of the critical value δ_{crit} in the experiment almost does not change the values of ion damping rate. Thus, we can say that the small shear can stabilize the unstable drift wave with the aid of a finite plasma length effect, and that the wave is stabilized by the parallel ion Landau damping. If we define the critical shear which is given by $\gamma/\omega^* \simeq 0$, its value should be expected to be smaller than that given by Eq.(1).

In conclusion, the ion temperature is controlled by using the ion-neutral-collisional cooling method, and the drift-wave stabilization by the magnetic shear is investigated carefully with the change of ion temperature. It is shown that the critical value for the shear stabilization is rather smaller than that estimated theoretically, but that near stabilization the ion Landau damping is effective when the effect of finite plasma lengh is considered.

The authors are grateful to Dr. I. Katsumata for the collaboration in measuring the ion temperature. One of the authors (Y. N.) is also indebted to Prof. Y. Hatta for his continuous encouragement.

This work was performed under the Collaborating Research Program of Institute of Plasma Physics, Nagoya University.

References

1. P. H. Rutherford and E. A. Frieman, Phys. Fluids, 10, 1007 (1967).
2. N. A. Krall and M. N. Rosenbluth, Phys. Fluids, 8, 1488 (1965).
3. L. D. Pearlstein and H. L. Berk, Phys. Rev. Letters, 23, 220 (1969).
4. J. N. Davidson and T. Kammash, Phys. Rev. A, 4, 1260 (1971).
5. F. F. Chen and D. Mosher, Phys. Rev. Letters, 18, 639 (1967).
6. P. E. Stott, D. F. Little, and J. Burt, Phys. Rev. Letters, 25, 996 (1970).
7. H. D. Pacher, G. W. Pacher, and S. Yoshikawa, Phys. Rev. Letters, 25, 1559 (1970).
8. H. D. Pacher and S. von Goeler, Phys. Fluids, 14, 1268 (1971).
9. The effects of ion temperature variations may be taken into in the experimental results through the ion Lamor radius.[6] Here, we mainly pay attentions to the ion Landau damping effect.
10. S. Nagao et al, Ann. Rev. I.P.P. Japan, April 1965-March 1966 (unpublished).
11. I. Katsumata, Japan J. Appl. Phys, 6, 123 (1967).
12. The measurement of P_G was performed at the head of the diffusion pump because of the limit of the experimental

apparatus. The actual pressure in the gas chamber is about an order of magnitude higher than P_G.

13. Y. Nishida, T. Dodo, T. Kuroda, and G. Horikoshi, (to be published). In this paper, the bounding orifices were not used and the convective mode was observed.

14. Under the present experimental condition, the critical shear given by Eq. (1) is more stringent than that the condition $R/L_s > (m/M)^{1/3} \simeq 0.05$.

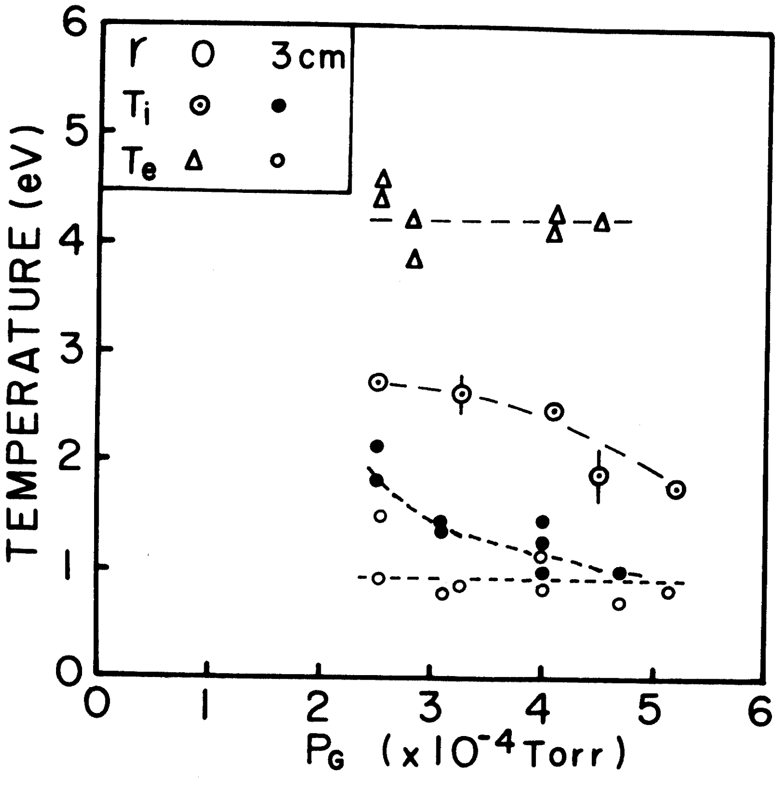

Fig.1 The ion and electron temperatures vs. the gas pressure. Closed circles are the ion temperatures measured by I.S.P., and dotted circles are that measured by electrostatic analyser. Open circles and triangles are the electron temperatures measured by Langmuir probe and I.S.P.. B_0 = 600 G.

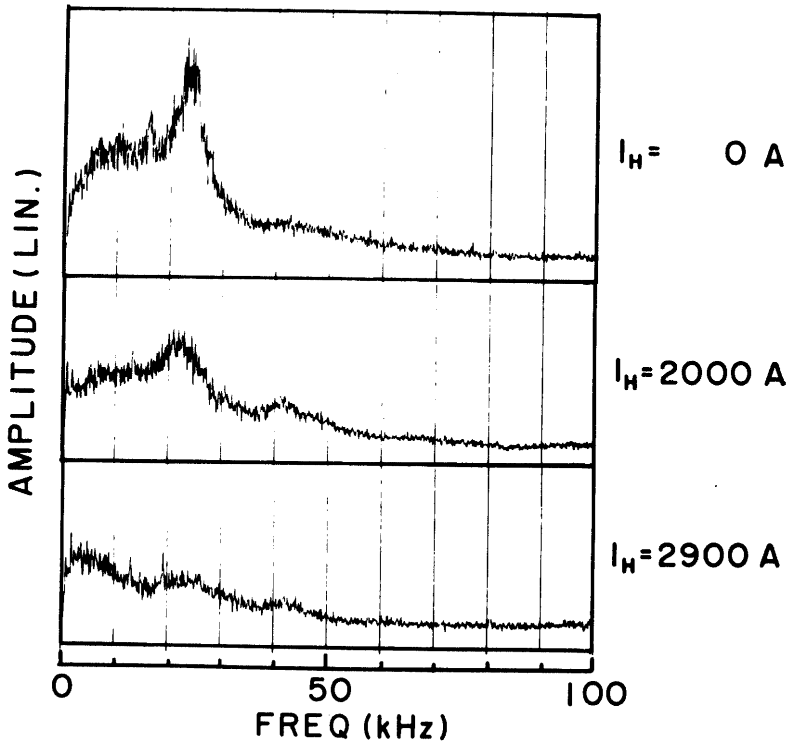

Fig.2 Fourier spectrums obtained by the auto-correlation method under the influence of the magnetic shear. Band width = 2100 kHz, B_0 = 600 G, P_G = 3.3 × 10^{-4} Torr, and T_i = 1.4 eV.

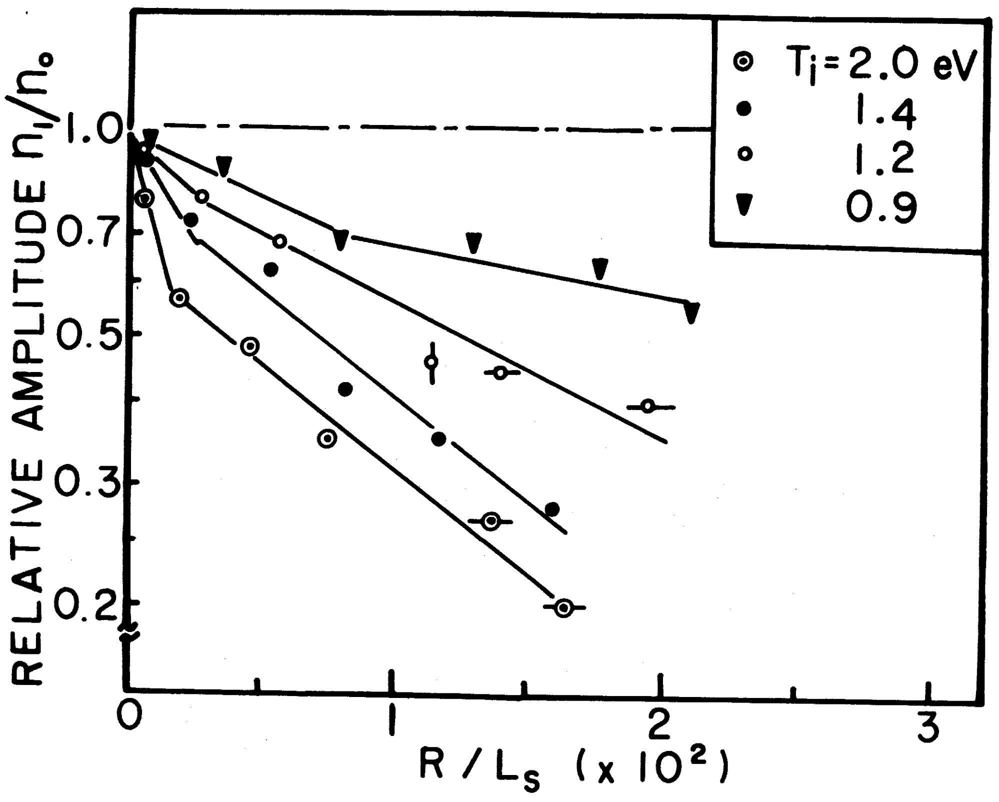

Fig.3 Fluctuation amplitude (n_i/n_0) vs. the magnetic shear. Amplitude is normalized at $R/L_s = 0$.