SHEAR STABILIZATION OF A POTASSIUM PLASMA*

Francis F. Chen and David Mosher
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey
(Received 26 January 1967)

Applying shear to the magnetic field confining a thermally ionized potassium plasma reduces the escape rate by as much as a factor of 30. This effect is accompanied by both a reduction and a localization of the low-frequency oscillations.

Three methods have been proposed for suppressing resistive and universal (drift) instabilities, which are harmful to plasma confinement: (a) use of magnetic wells with minimum average $\overline{B}$, (b) shortening the connection length between regions of good and bad curvature, and (c) use of large shear. This experiment is designed to test (c) in the absence of (a) and (b), which have been tested in multipoles.

An effectively fully ionized cylindrical potassium plasma with $kT = 0.22$ eV is created by thermal ionization in a long Q machine[1] with $L = 325$ cm, $R = 2.5$ cm, $B_z = 0$-4 kG. A shear field B_θ is provided by a current I_s (0-5 kA) flowing in a 1-cm-diam aluminum tube strung through 1.3-cm-diam holes in the hot tungsten endplates. B_θ thus falls as r^{-1}, and the shear as r^{-2}; the curvature is unfavorable everywhere outside the density maximum. The end sheaths are kept electron-rich for good line tying[2]; thus ordinary flute instabilities are excluded. The atomic beams directed at the endplates are collimated by annular slits and are equal within 5%. Plate temperature is uniform to 0.2%; B_z to 1%. The axial conductor is kept straight to 0.2 mm by tension and is aligned with B_z to 0.5 mm. It is anodized so that the potential drop along it does not appear in the plasma. Base pressure is 5×10^{-6} Torr. At 4 kG, r_L/R is 0.04 for ions. The ion-electron mean free path λ_{ei} varies from 100 to 0.3 cm as the density n varies from 10^9 to 3×10^{11} cm^{-3}.

With $I_s = 0$, a continuous spectrum of low-frequency oscillations is observed on the floating potential of and the saturation ion (J_+) and electron (J_-) currents to Langmuir probes. We interpret this to be the spectrum of resistive drift waves.[3] The radial electric field in such a plasma causes the drift velocity v_{de} to be ≈ 0 in the laboratory frame.[4] Consistent with this, the spectrum is peaked near 0 and extends to ≈ 5 kHz. We present here results for values of B_z such that $n_1/n_0 = O(1)$ in the absence of shear, where n_1 is the perturbation in n.

Figure 1 shows a low-density example of the dramatic increase in density with shear. Except at the largest I_s, the peak density is a measure of the effective cross-field diffusion rate because (1) the equilibrium density computed from endplate recombination would be much higher than that observed, (2) the density profiles do not resemble the distribution of input flux, and (3) the density increases with B_z. From such data we have computed an effective $D_\perp$ as follows. The peak density is computed from J_+ by a combination of Langmuir's orbital theory and Lam's theory[5] which takes into account the nonlinearity of the n-J_+ relation

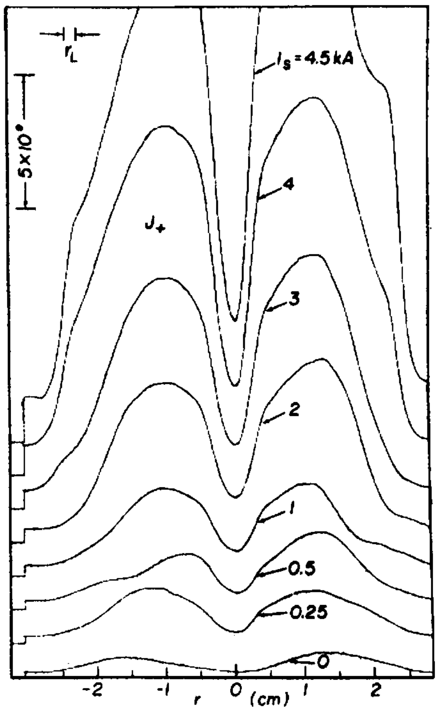

FIG. 1. Radial profiles of ion-saturation probe current J_+ for various values of shear current I_s in the axial conductor. Note that the baseline has been shifted for successive curves. B_z was 4 kG. The depression at the center is due to the presence of the axial conductor; the probe was moved slightly off-axis so as to miss it.

near $r_{\text{probe}} \approx \lambda_D$. The input flux Φ is measured by dropping negative cold plates into the plasma near the ends; these plates collect all the ions which are produced. The z dependence of the density profiles is neglected, and an average density-gradient scale length r_0 is either estimated from the observed profiles or calculated theoretically from a simple diffusion equation. The equation of continuity then yields $D_\perp$.

We have further taken out the B dependence by normalizing $D_\perp$ to the Bohm coefficient $D_{\text{B}} \equiv ckT/[16e(B_z^2+B_\theta^2)^{1/2}]$. The result is plotted against the shear parameter $\theta \equiv |r(\partial/\partial r)(B_\theta/rB_z)|r_0$, evaluated at $r = 2.1$ cm, and is shown in Fig. 2. Also shown are estimates of classical losses due to resistive diffusion and endplate recombination. Other losses—diffusion from ion-ion, ion-neutral, and ion-endplate collisions and recombination on probes—are relatively minor. The large error bars indicate the systematic error in the vertical scale due to the use of probes for absolute density measurements. The smaller relative errors are due to changes in r_0 with I_S, changes in sheath potential with n (although it is never allowed to change sign), nonreproducibility, and the outgassing effect. The latter is an increase in Φ for $I_S \gtrsim 4$ kA because the axial conductor warms up and evaporates K atoms deposited on its surface; this has been evaluated and corrected for. Figure 2 shows that at low density $D_\perp$ is reduced by a factor of 30 for $\theta \approx 0.3$, while at high density the level of purely classical losses is reached.

Figure 3 shows the effect of shear on the magnitude and radial distribution of fluctuations $\tilde{J}_-$ in electron saturation current in the entire range 5 Hz-500 kHz. At $I_S = 0$, large fluctuations exist throughout the plasma. At $I_S = 1$ kA, drift waves are localized to the region of the outer density gradient. At this shear, $D_\perp$ is considerably reduced even though the peak oscillation amplitude is not. At $I_S = 2$ and 4 kA, the drift wave peaks become smaller and narrower and are pushed out to the region of weakest shear. At 4 kA, the small peaks are due to rather coherent low-frequency oscillations with $n_1/n_0 = O(10\,\%)$; outside the peaks, n_1/n_0 is $O(1\,\%)$. There is a tendency for the density profile to be locally flattened at a drift-wave peak. Figure 3 shows that the reduction in $D_\perp$ is apparently caused by both suppression and localization of the oscillations, as theory would predict.

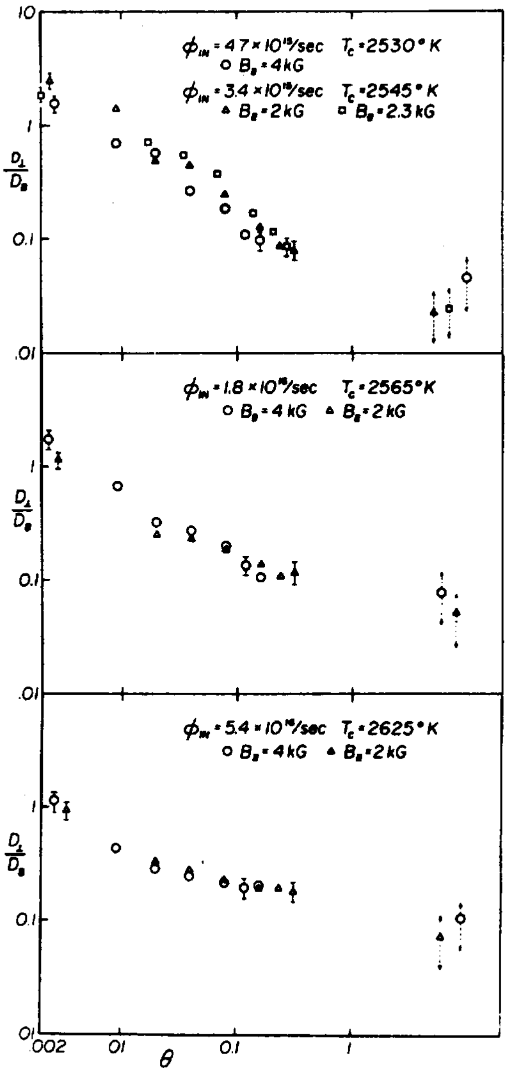

FIG. 2. Variation of normalized diffusion coefficient $D_\perp$ with shear parameter θ for three values of total input flux Φ (ions/sec). The peak densities at $I_S = 0$ for the three cases are, roughly, 4×10^{10}, 7×10^9, and 2×10^9 cm^{-3}. The points at extreme left are for zero shear; error bar is relative error for each curve. The points at extreme right are estimates of classical losses; error bar there indicates absolute error in $D_\perp$.

Detailed comparison with theory is difficult because $D_\perp$ decreases gradually with θ, and no critical value θ_c occurs for which all oscillations suddenly cease. This is because θ varies with r, and also θ_c itself may vary with θ if it depends on n or $k_\perp$, which vary with θ. However, we can compare the theoretical θ_c with the minimum value of θ (at $r = R$) measured

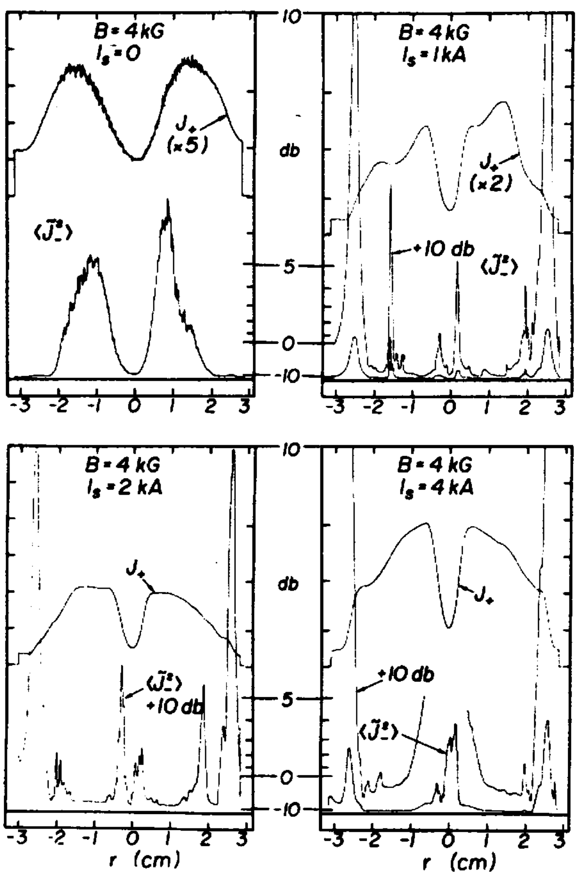

FIG. 3. x-y recorder traces of the radial profiles of density (actually J_+) and mean-square oscillation amplitude, for different I_s. The large peaks at the edges are high-frequency oscillations not discussed here. Note that at $I_s = 4$ kA the density profile resembles the input flux distribution, indicating that endplate recombination dominates. The reduction in noise is larger than it appears, because $\tilde{J}_-$ has not been normalized to the density.

when the loss rate approaches the classical one. The theory for this experiment has been worked out by Chen,[3] who found that normal modes for resistive drift waves are stabilized by ion Landau damping for

$$\theta > \theta_c \approx 2^{3/2}(r_L/r_0), \tag{1}$$

and that nonconvective quasimodes require $\theta > \theta_c \approx 2^{3/2}$. Taking $r_L = 1$ mm and $r_0 = 1.6$ cm (note the definition of r_0 in cylindrical geometry[3]), we find that Eq. (1) yields $\theta_c \approx 0.16$, which is in reasonable agreement with Fig. 2. A recent careful treatment of resistive quasimodes by Coppi et al.[6] shows that they are highly convective and would be stabilized by

$$\theta > \theta_c \approx \frac{1}{3N}\left(\frac{m}{M}\frac{\nu_{ei}}{k_\perp v_{de}}\right)^{1/2}. \tag{2}$$

Taking the smallest imaginable values for $k_\perp$ and N (the number of e-foldings of the wave growth, taken as 3), we find from this $\theta_c \approx 0.007$ for $n = 10^{10}$ cm^{-3}, which does not agree with experiment. Furthermore Eq. (2) predicts $\theta_c \propto (nB)^{1/2}$, for which there is no evidence. On the other hand, Eq. (1) predicts $\theta_c \propto B^{-1}$, for which there is a slight indication in the bottom graph of Fig. 2. If this dependence were real, shear stabilization would be much more effective at high fields.

The criterion $\nu_{ei} \gtrsim v_{de}/r_0$ given by Coppi et al.[6] for the applicability of collisional theory is well satisfied in this experiment, but nonetheless we have evaluated θ_c for collisionless normal modes[7] and quasimodes.[6,8] These all turn out to be too small. In our plasma the centrifugal force[3] and field curvature due to shear could cause resistive gravitational interchange instabilities. However, using a criterion of Coppi et al.,[6] we find that these modes are stable for $0.006 < \theta < 14$ at $n = 10^{10}$.

We have shown that shear alone can greatly reduce the anomalous loss rate in a resistive plasma. The effectiveness of shear seems to come from the localization of ordinary normal modes. The amount of shear required, however, is rather large ($\theta > 0.1$); and it may be more efficient to use (a) and (b) of paragraph 1 for elimination of drift modes. Nonetheless, shear stabilization may still be useful because it can be applied without the use of conductors inside the plasma.

*This work was performed under the auspices of the U. S. Atomic Energy Commission, contract No. AT(30-1)-1238.

[1]N. Rynn, Rev. Sci. Instr. 35, 40 (1964).

[2]F. F. Chen, J. Nucl. Energy: Pt. C 7, 399 (1965).

[3]F. F. Chen, Phys. Fluids 9, 965 (1966).

[4]F. F. Chen, Phys. Fluids 9, 2534 (1966).

[5]F. F. Chen, in Plasma Diagnostic Techniques, edited by R. H. Huddlestone and S. L. Leonard (Academic Press, Inc., New York, 1965), Chap. 4.

[6]B. Coppi, G. Laval, R. Pellat, and M. N. Rosenbluth, International Atomic Energy Agency International Centre for Theoretical Physics, document No. IC/65/88, Trieste, 1965 (unpublished).

[7]N. A. Krall and M. N. Rosenbluth, Phys. Fluids 8, 1488 (1965).

[8]P. Rutherford and E. A. Frieman, Plasma Physics Laboratory report No. MATT-476, 1967 (unpublished).