the electrons to a drift velocity much larger than the electron thermal velocity before turbulence can develop. Quantitatively this condition can be written as

$$(e/m)E_0(10/\gamma) > \bar{v}_e, \quad (5)$$

where $\gamma \simeq \omega_{pe}(m_e/m_i)^{1/3}$ is the electron-ion two-stream instability growth rate and we have assumed that ten e-foldings are necessary for the turbulence to develop. For the experimental conditions of Hamberger and Friedman,[1] Eq. (5) requires an electric field of order 100 V/cm, which is in the range of the fields obtained in the experiment.

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[1]S. M. Hamberger and M. Friedman, Phys. Rev. Lett. 21, 674 (1968).

[2]J. Orens, J. Boris, J. Dawson, and R. Shanny, Bull. Amer. Phys. Soc. 15, 533 (1970).

[3]N. Rostoker and M. N. Rosenbluth, Phys. Fluids 3, 1 (1960).

[4]T. E. Stringer, J. Nucl. Energy, Part C 6, 267 (1964).

DRIFT WAVES AND PLASMA DIFFUSION IN A SHEAR-STABILIZED Q MACHINE

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The effects of magnetic shear on unstable drift waves are studied in a straight $l=3$ stellarator. Increasing the shear reduces the amplitude of the instability and also the cross-field diffusion coefficient.

The stability of a low-β plasma magnetically confined in a toroidal stellarator may be seriously weakened by unstable drift waves. These well-known plasma oscillations are associated with the spatial inhomogeneity which is inherent in confinement. The growth of the instability is due to a restriction of the electron parallel motion which may be caused either by collisional resistivity or by collisionless resonant-particle effects.

Theory predicts that drift waves should be stable in a strongly sheared magnetic field. The shear stabilization of collisional drift waves has been studied experimentally by Chen and Mosher[1] in an annular plasma column surrounding a rod carrying current parallel to the main magnetic field. The drift waves disappeared and the peak plasma density increased as the current in the rod was increased.

We have investigated the shear stabilization of drift waves by means of stellarator-type helical windings external to the plasma. A straight stellarator was constructed for these experiments since in a toroidal device the shear cannot be easily varied over a very wide range of values without disturbing the toroidal equilibrium of the plasma.

The essential features of the experimental apparatus (STAMP) are shown in Fig. 1. Lithium or sodium plasmas are produced by thermally ionizing a beam of neutral atoms directed onto a rhenium plate (diameter 7.5 cm) heated to over 2000°K. The basic principles of such a Q machine are well known and the detailed design of the sources used on STAMP has been reported previously.[2] Two identical sources which can be moved axially produce a plasma whose length may be varied between 40 and 400 cm. The axial magnetic field is variable up to 4000 G and at that field lithium ions have a Larmor radius of

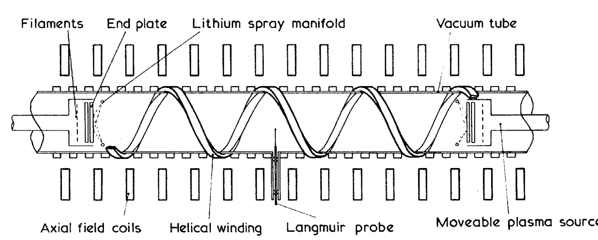

FIG. 1. Schematic of the STAMP experiment. For clarity only one of the six helical conductors is indicated.

0.3 mm. The periodicity of the $l = 3$ helical winding is 80 cm and the maximum current is 48 000 A.

Computations of the helical magnetic fields are in good agreement with measurements using an electron beam to trace out field lines onto a fluorescent screen. The magnetic field lines lie on a nested set of trefoil-shaped cylinders. The rotational transform ι has a nearly parabolic radial dependence and at the separatrix the transform per winding period is 2π. It is convenient to express the magnetic shear in terms of the shear length $L_s = [(2\pi/80)r d\iota/dr]^{-1}$ which varies roughly as the inverse square of the radius and is about 7 cm at the separatrix.

When the current in the helical winding is zero, we observe spontaneously occurring oscillations of the plasma density $\tilde{n}$ and potential $\tilde{\varphi}$ which we have previously identified as collisionless drift waves.[3] At a density of 10^8 cm^{-3} the electron-ion collision length $\lambda_{ei} = 600$ cm, and electron-ion encounters within the length of the column are too infrequent to generate collisional drift waves. The density and potential oscillations have peak rms amplitudes n_1 and φ_1 close to the radius r_1 where the density scale length $\Delta = [d(\ln n_0)/dr]^{-1}$ is smallest. Typically $n_1/n_0 = e\varphi_1/kT = 10\text{-}20\,\%$.

We observe that the amplitude of the unstable drift waves is reduced as the current in the helical winding is increased. A typical comparison, with and without shear, of the radial profiles of mean density n_0 and rms level n_1 is shown in Fig. 2. In this case the effective shear was $\Delta/L_s = 0.05$.

A necessary stability condition for drift waves to eliminate the normal modes has been calculated by Krall and Rosenbluth[4]: $\Delta/L_s > a_i/\Delta$. It is also necessary to ensure that even if the normal modes are stable, the local growth of nonthermal fluctuations does not lead to an unacceptable level of instability. To prevent this Rutherford and Frieman[5] have calculated that $\Delta/L_s > (m_e/m_i)^{1/3}$ and in general both of these conditions should be satisfied for complete stability. However, in our experiments with a lithium plasma the normal-mode stability condition is harder to satisfy since $(m_e/m_i)^{1/3} = 1/20$ and typically $a_i/\Delta \geqslant 1/10$. In Fig. 3 the relative rms amplitude n_1/n_0 is plotted against $s = \Delta^2/L_s a_i$. Extrapolating the experimental results suggests that n_1/n_0 would reduce to zero in the vicinity of $s = 1$.

Figure 2 shows that there is an increase of

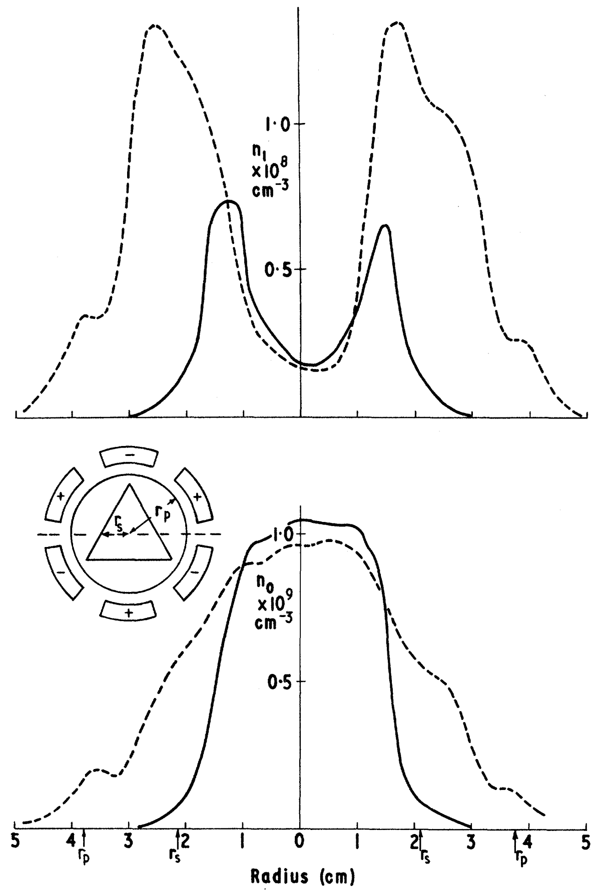

FIG. 2. Radial profiles of mean density n_0 and rms level n_1 compared for a shear-free lithium plasma (dashed curve) and for a helical current of 30 000 A (full curve). In the shear case, the profiles were measured parallel to the base of the separatrix triangle (see inset diagram) which lies just inside the diameter of the end plates. The length of the column was 200 cm and the axial field 1300 G.

about 10 % in the central plasma density when the shear is switched on. This apparently small increase in fact corresponds to a significant reduction in the cross-field diffusion rate which is masked by the relatively high axial loss rate. Axial losses are about 5 times greater than radial losses in this collisionless plasma since the ions are not trapped in the potential well formed by the end-plate sheaths and the recombination probability of lithium on rhenium is about 60 %. The drift waves produce a radial plasma flux

$$j_\perp(\text{wave}) = \langle \tilde{n}\tilde{E}_\theta/B\rangle = (1/rB)d\langle \tilde{n}\tilde{\varphi}\rangle/d\theta.$$

We have measured $\langle \tilde{n}\tilde{\varphi}\rangle$ using two probes with a variable separation and we observe that the density wave leads the potential wave, typically by a phase angle of 20 deg. This results in an

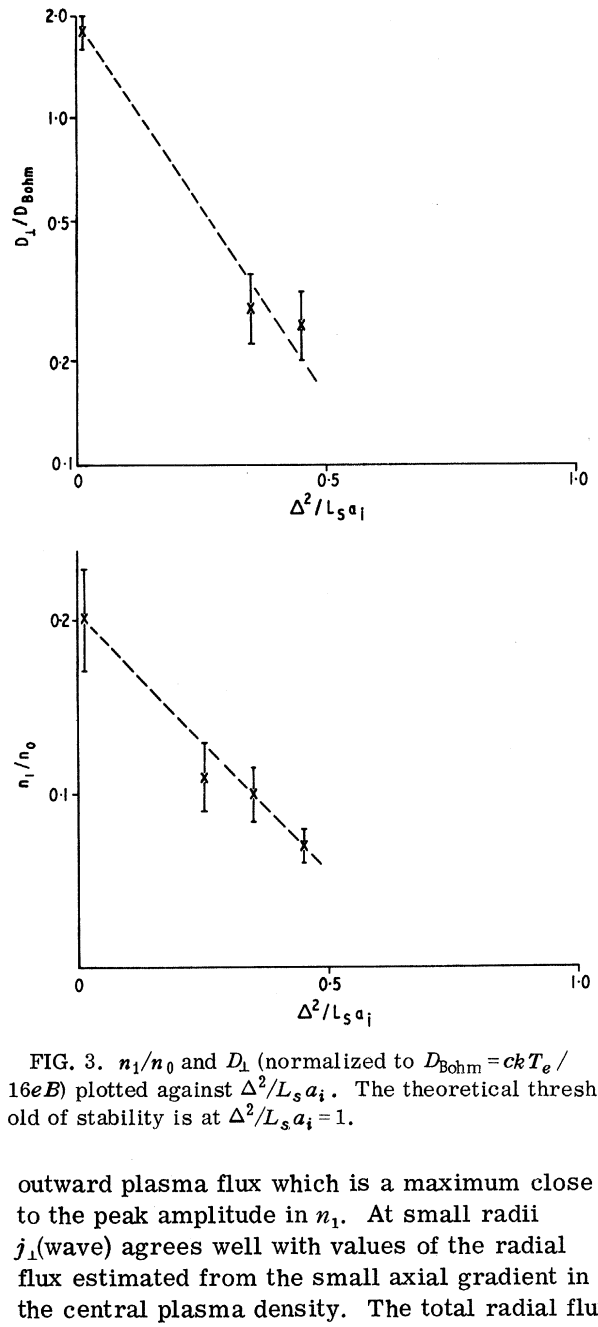

FIG. 3. n_1/n_0 and $D_\perp$ (normalized to $D_{\mathrm{Bohm}} = ckT_e/16eB$) plotted against $\Delta^2/L_s a_i$. The theoretical threshold of stability is at $\Delta^2/L_s a_i = 1$.

outward plasma flux which is a maximum close to the peak amplitude in n_1. At small radii $j_\perp$(wave) agrees well with values of the radial flux estimated from the small axial gradient in the central plasma density. The total radial flux at the outside edge of the plasma, $j_\perp$(total), was measured on a cylindrical ion-biased collector positioned just outside the radius of the end plates ($r_p = 3.75$ cm). The value of $j_\perp$(total) measured in this way is equal to the peak value of $j_\perp$(wave) which indicates that the radial plasma losses are determined by the amplitude of the unstable drift waves. Close to the edge of the end plates, however, $j_\perp$(wave) falls off, indicating an additional loss mechanism in this region. This is probably due to convective plasma motions caused by slight asymmetries of the end plate temperature.[6] Asymmetries as small as 10°K would be sufficient to provide the observed loss rate at the edge of the plasma column. We have not made a detailed investigation of the convective processes, but our measurements of $j_\perp$(wave) and $j_\perp$(total) are consistent with a radial transport model proposed by Chen[7] in which the drift waves sustain the radial plasma flux in the body of the column although additional mechanisms, such as convection at the edge of the column, are responsible for the final stage of transport out to the walls.

The radial diffusion coefficent $D_\perp$ has been calculated from these measurements of the fluxes $j_\perp$(wave) and $j_\perp$(total). In a uniform field $D_\perp$ is nearly inversely proportional to the field strength and is of the order of $D_{\mathrm{Bohm}} = ckT/16eB$. This is roughly two orders of magnitude higher than the coefficient of diffusion due to binary collisions. The accurate calculation of $D_\perp$ in the sheared configuration is difficult due to the complicated topology of the magnetic fields, but approximate values can be estimated taking mean values for the density gradient and show an improvement in $D_\perp$ as the effective shear is increased. We have not investigated in detail the dependence of $D_\perp$ (with shear) on either the axial magnetic field or the column length.

The main limitation in extending the measurements closer to the theoretical threshold of stability at $s = 1$ is that the density gradient steepens rapidly as the helical winding current is increased. This reduces the effective shear across the density gradient to much less than the total shear between the center of the tube and the separatrix. The plasma density profile is determined by the spray of lithium atoms onto the end plates and ideally this should match the trefoil shape of the magnetic surfaces. We are modifying the spray pattern in order to make the density gradient less steep and thus improve the effectiveness of the magnetic shear. We are also improving the circular symmetry of the end-plate temperature in order to reduce the convective losses at the edge of the end plates.

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[1]F. F. Chen and D. Mosher, Phys. Rev. Lett. 18, 639 (1967), and in *Proceedings of the Conference on Physics of Quiescent Plasmas, Frascati, Italy, 1967* [Laboratori Gas Ionizzati (Association Euratom Comitato Nazionale per l'Energa Nucleare), Frascati, Italy,

1967].

[2]J. Burt, P. F. Little, and P. E. Stott, Plasma Phys. 11, 789 (1969); also Culham Laboratory Report No. CLM-R98 (unpublished).

[3]P. E. Stott, P. F. Little, and J. Burt, in *Proceedings of the Third European Conference on Controlled Fusion and Plasma Physics, Utrecht, The Netherlands, June 1969* (Wolters-Noordhoff Publishing, Groningen, The Netherlands, 1969).

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

[5]P. H. Rutherford and E. A. Frieman, Phys. Fluids 10, 1007 (1967).

[6]D. Mosher and F. F. Chen, Phys. Fluids 13, 1328 (1970).

[7]F. F. Chen, in *Proceedings of the International Conference on Physics of Quiescent Plasmas, Paris, 1968* (Ecole Polytechnique, Paris, 1969), Vol. II, p. 159.

DEPENDENCE OF "ANOMALOUS" CONDUCTIVITY OF PLASMA ON THE TURBULENT SPECTRUM

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The scaling laws for "anomalous" conductivity seen in a turbulent plasma are shown to depend on the type of electrostatic fluctuation spectrum present, which in turn depends on the relative drift velocity between ions and electrons.

In the last few years there have been several reports of experimentally measured values of plasma conductivity which are much smaller than the so-called "classical" value based on binary Coulomb collisions. Most such reports relate to plasma in which there is a suprathermal level of electrostatic fluctuation, arising from some instability excited either deliberately (as in turbulent heating experiments[1-3] or collisionless shocks[4]) or inadvertently (as in toroidal containment systems[5] or theta-pinches[6]). Since a wide range of experimental parameters have been involved, and the theory of turbulent plasma is still in an exploratory stage, some confusion has arisen regarding the scaling laws which govern the conductivity and their relation to known plasma instabilities, etc. In particular, for the class of experiment in which the turbulence arises as the result of applying a strong electric field to a weakly collisional plasma, three separate (though related) mechanisms have been proposed to explain the observed effects based on the excitation of different forms of electrostatic instability. It is the purpose of this paper to show that certainly two, and probably all three, of these situations can occur for different plasma conditions even in the same apparatus, the scaling laws (i.e., variation of conductivity with density, applied field, ion mass, etc.) being different for each.

Very briefly, the three exciting mechanisms referred to above are these:

(1) The excitation of ion-sound waves by induced Cherenkov emission from the drifting electrons when the drift velocity $v_d \geq c_s = (T_e/M)^{1/2}$, the sound speed.[7-9] (T_e is the electron temperature in energy units, M the ion mass.) The frequency spectrum which develops as a result of nonlinear effects has been discussed for this case by Kadomtsev[8] and Tsytovich,[9,10] and, as would be expected, lies in the frequency range $<\omega_{pi}$, the ion plasma frequency.

(2) The development of a hydrodynamic instability as predicted by Budker[11] and Buneman[12] resulting from electron-ion counterstreaming. In a warm plasma this is expected when $v_d \gtrsim v_e = (2T_e/m)^{1/2}$, the electron thermal speed, and is characterized by fastest initial growth at frequencies around $\omega^* = \frac{1}{2}(m/M)^{1/3}\omega_{pe} = \frac{1}{2}(M/m)^{1/6} \times \omega_{pi}$.

(3) Various forms of beam-plasma instability resulting from the formation of a secondary "runaway" beam of electrons which interacts with the background electrons. In the laboratory frame these could have frequencies $\omega \approx \omega_{pe}$ if $\omega_{pe} \gg \omega_{ce}$ (the gyrofrequency) or $0 < \omega < \omega_{pe}$ if $\omega_{pe} < \omega_{ce}$.[13]

We have studied the spectrum of short-wavelength potential fluctuations in a toroidal apparatus, already well described,[14] using calibrated high-impedance floating double probes (spacing $\leq$1 mm) with frequency response up to 2 GHz. For comparison, the ion plasma frequency in these experiments was 100-700 MHz, and the Debye distance of order 10^{-3}-10^{-2} cm. The technique used was to record the potential difference V between the probe electrodes directly on an oscilloscope (Tektronix model 519), and to obtain the power spectra $\langle V^2(\omega)\rangle$ (Fig. 1) by computing numerically the Fourier transform of