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

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A B S T R A C T

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

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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[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 0.3 mm.

The periodicity of the $\ell = 3$ 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 $\Delta = [d(\log n_0)/dr]^{-1}$ 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 non-thermal fluctuations does not lead to an unacceptable level of instability. To prevent this Rutherford and Frieman[5] have calculated that $\Delta/L_S > (m_e/m_i)^{\frac{1}{3}}$ 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 $(m_e/m_i)^{\frac{1}{3}} = 1/20$ and typically $a_i/\Delta \geq 1/10$. 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 $s = 1$.

There is a corresponding decrease in the rate of crossfield diffusion. The central plasma density increases slightly but only by about 10% since recombination losses at the endplates exceed the radial losses in this plasma. The radial plasma flux can be calculated from the cross-correlation of the density and potential oscillations

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

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 degrees. This results in an 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 radial flux at the outside edge of the plasma was measured on a cylindrical ion-biased collector positioned just outside the radius of the endplates $(r_p = 3.75 \text{ cm})$. The total flux measured in this way is equal to the peak value of $j_\perp$ (wave). Close to the edge of the endplates $j_\perp$ (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 endplate temperature[6]. Asymmetries as small as 10^{0}K would be sufficient to provide the observed loss rate at the edge of the plasma column. Our measurements of plasma diffusion are consistent therefore with transport due to unstable drift waves in the body of the plasma assisted by convection close to the edge of the column.

The radial diffusion coefficient $D_{\perp}$ has been calculated from these flux measurements. In a uniform field $D_{\perp}$ is nearly inversely proportional to the field strength and is of the order of $D_{Bohm} = ckT/16$ eB. This is roughly two orders of magnitude higher than the coefficient of diffusion due to binary collisions. 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 centre of the tube and the separatrix. The plasma density profile is determined by the spray of lithium atoms onto the endplates 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 endplate temperature in order to reduce the convective losses at the edge of the endplates.

REFERENCES

1. F.F. Chen, Int. Conf. on Physics of Quiescent Plasmas, Frascati, (1967).

2. J. Burt, P.F. Little, and P.E. Stott, Plasma Phys. 11, 789 (1969); also Culham Laboratory Report CLM-R98.

3. P.E. Stott, P.F. Little, and J. Burt, Proc. 3rd European Conference on Controlled Fusion and Plasma Physics, Utrecht, p.125, (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. Chen, Princeton University Report, Matt 691, (1969).

Filaments End plate Lithium spray manifold   Vacuum tube

Axial field coils   Helical winding   Langmuir probe   Moveable plasma source

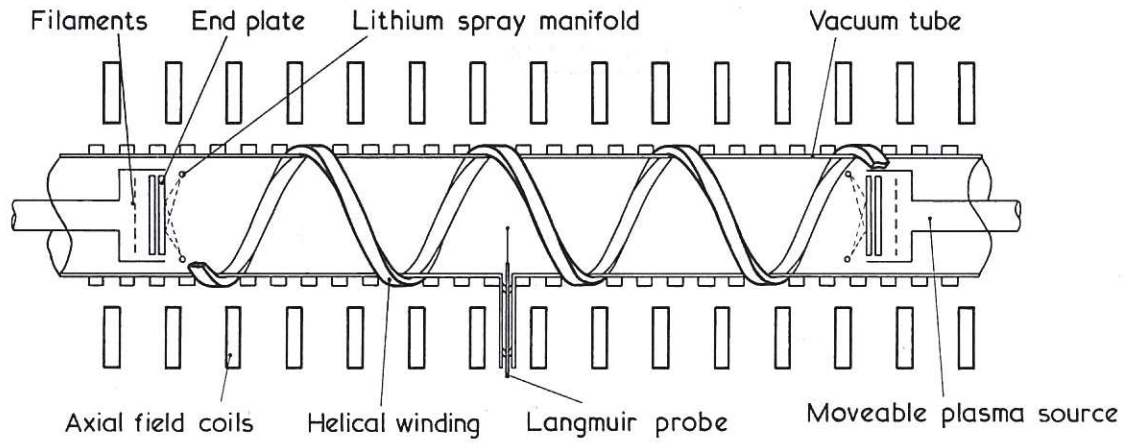Fig.1   (CLM-P 242)
Schematic of the STAMP experiment. For clarity, only one of the six helical conductors is indicated.
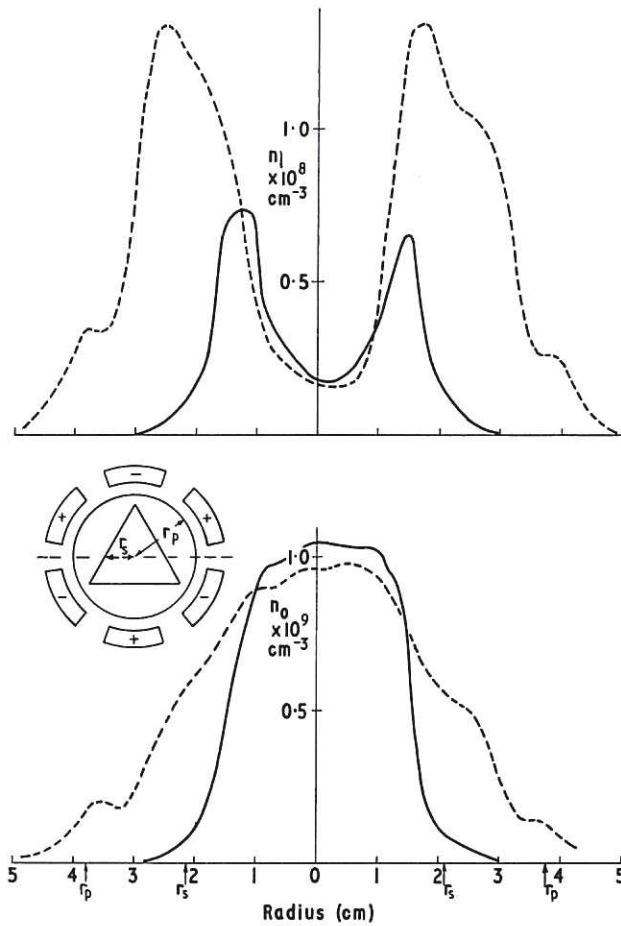

Fig.2   (CLM-P 242)
Radial profiles of mean density n_0 and rms level n_1 compared for a shear free lithium plasma (dashed curve) and for a helical current of 30,000A (full curve). In the shear case, the profiles were measured parallel to the base of the separatrix triangle (see inset diagram) which lies just inside the diameter of the endplates. The length of the column was 200cm and the axial field 1300G.
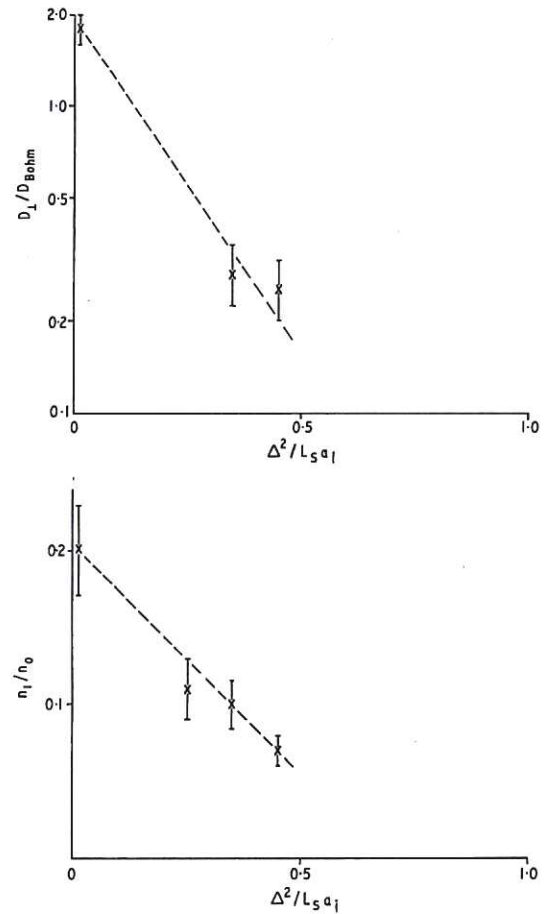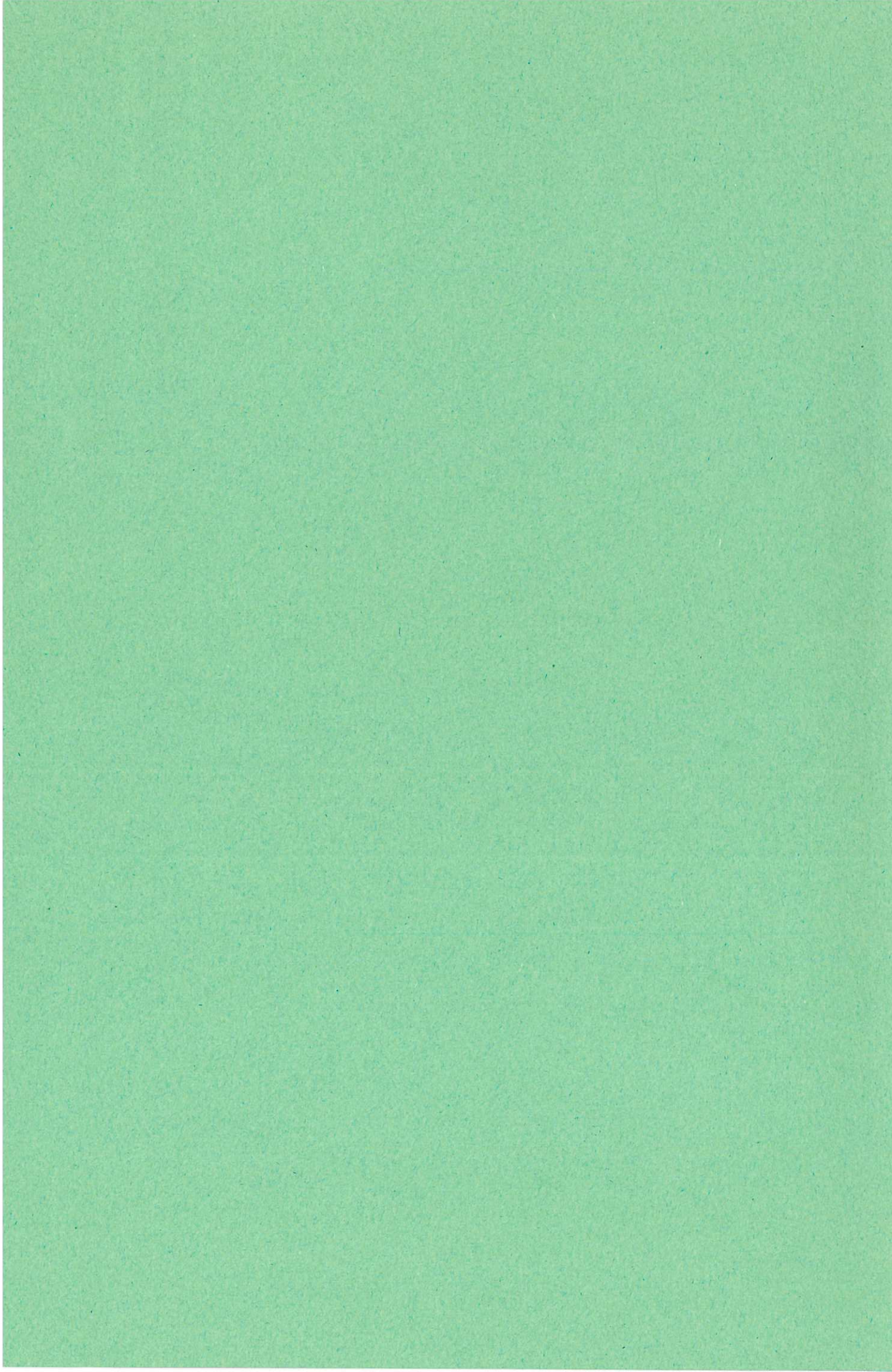

Fig.3   (CLM-P 242)
n_1/n_0 and $D_\perp$ (normalised to $D_{Bohm} = ckT_e/16eB$) plotted against $\Delta^2/L_s\, a_i$. The theoretical threshold of stability is at $\Delta^2/L_s\, a_i = 1$.