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Report

A SUMMARY OF CONTAINMENT EXPERIMENTS ON THE PROTO-CLEO STELLARATOR

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by

D.J. LEES

ABSTRACT

This report collects together results on the containment of plasma injected into the PROTO-CLEO stellarator, some of which have been previously presented as conference papers. The importance of fluctuations on plasma containment is also discussed and an attempt made to arrive at momentum balance for the ions and electrons. It is concluded that although plasma can be contained for periods as long as expected on the basis of loss solely by collisions, it cannot be conclusively demonstrated that this is the sole mechanism of plasma loss, since evidence for the existence of the diffusion driven current cannot be found.

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1. INTRODUCTION

The programme for the PROTO-CLEO stellarator experiment has largely been devoted to a study of the containment of a low β plasma injected into a high shear stellarator. It was eventually extended to study transit time magnetic pumping in stellarator geometry. These results will be reported elsewhere and we do not propose to comment on them in this paper. Many of the containment results have already been reported[1-5] and a description of the apparatus has been given in an earlier paper[6]; the main purpose this paper serves is thus to collect together the containment information in such a way that it is easily accessible by other workers in this field.

2. EXPERIMENTAL RESULTS

The main parameters of the assembly are summarized in Table I. It will be seen that three different helical configurations have been used, namely $\ell = 3$, 7 and 13 field periods and $\ell = 2$, 6 field periods. Each winding has the same major radius, 40 cm and approximately the same minor radius of 10 cm. The toroidal field used has values in the range 0–5 kG, while the helical winding current which determines the separatrix and the rotational transform has been varied over the greatest range possible. A limiter has been used only for $\ell = 2$, so that the separatrix generally determines the plasma edges with a region of moderate shear coincident with the steepest density gradient.

TABLE I

PARAMETERS OF TRAP

	PROTO-CLEO I	PROTO-CLEO II	PROTO-CLEO III
Major radius (true toroidal) (cm)	40	40	40
Helical winding mean radius (cm)	9	10	9.3
Separatrix radius (cm)	5	5	7
Number of field periods on torus	$\ell = 3$ 7	$\ell = 3$ 13	$\ell = 2$ 6
Maximum toroidal field B_φ kG	0–3	0–5	0–3
Rotational transform computed at plasma boundary	0–1.2π	0–2.1π	0–1.6π
Useful time duration of fields	10 ms	10 ms	10 ms

The majority of the containment results have been obtained by studying the plasma injected into the trap from an occluded hydrogen $j \times B$ plasma gun. Some results are obtained from a similar gun but with a gas feed, of a type developed by Ashby[7], while electron cyclotron resonant heating of the injected plasma was used to obtain the results at lowest collision frequencies.

Finally, a 10 J neodymium-glass laser beam, focused on to a solid target of lithium, beryllium or solid hydrogen has generated higher density (but, in general, colder) plasmas. A summary of the plasma parameters produced by each method is given in Table II.

TABLE II

PLASMA PARAMETERS

Method	n cm^{-3}	T_e(eV)	T_i(eV)
Titanium gun (Hydrogen plasma)	10^{10} - 10^{11}	~ 4	5 - 25
Titanium gun and E.C.R.H.	2×10^9 - 2×10^{10}	5 - 10	~ 20
Gas fed gun (Hydrogen plasma)	10^{11} - 5×10^{12}	~ 3	~ 10
Laser plasma Lithium and Beryllium	10^{11} - 5×10^{12}	~ 2	~ 4

3. DIAGNOSTICS

Plasma parameters have generally been measured in the same way for all experiments. Electron density is given by a 16 mm microwave interferometer, allowance being made for density distribution. Electron temperature is inferred from a Langmuir probe and ion temperature from a multi-gridded analyser placed at the separatrix(8). Neutral density has been obtained by the use of a specially developed fast responding ionization gauge. Electric fields and density fluctuations are measured by multiple probes. The electric field fluctuations are inferred from changes in floating potential. Some measurements of true plasma potential have been made(9); these showed that, as expected, $V_p - V_f$ depends on the electron temperature. Thus in making our inference about electric fields we do assume that the fluctuations of electron temperature can be neglected.

Measurements of the variation of density and floating potential around magnetic surfaces have been made using a multi-pin probe which could be rotated, so as to sample the whole plasma region.

Particle containment time is assumed as equal to the e-folding time for density decay. The measurements of neutral density show that for a well getter-pumped system, the plasma is generally about 50% ionized. Since $T_e \sim 4$ eV the error in containment time due to recycling is less than 10%.

4. SCALING LAWS FOR CONTAINMENT

The diffusion coefficient for a collisional toroidal plasma is given as :-

$$D_{ps} = \frac{1.66 \times 10^{-5}\, n \ell n \Lambda}{T_e^{\frac{1}{2}} B_\varphi^2} \left(1 + \frac{T_i}{T_e}\right) \left(1 + \frac{1}{t^2}\right) \quad \left[\mathrm{cm}^{-3},\, \mathrm{eV},\, \mathrm{gauss}\right] .$$

In converting this diffusion coefficient to a containment time for an $\ell = 3$ stellarator, account must be taken of the variation of D with radius, since t is also a function of the radius. The relationship is $\tau_{ps} = \frac{a^2}{D_2}\left(\frac{4}{15}\right)^2$ where a is plasma radius, D_2 is the value of D_{ps} calculated at maximu $t (t \propto r^2)$.

Figure 1 shows a summary of results of containment measurements in the $\ell = 2$ and $\ell = 3$ versions of PROTO-CLEO. In these graphs containment time has been normalized to the value τ/τ_{ps}. The abscissa is the ratio of connection length to electron ion mean free path which is defined as :-

$$\lambda_{ei} = 4.0 \times 10^{13} \frac{T_e^2}{n \ell n \Lambda} \quad \left[\mathrm{cm},\, \mathrm{eV},\, \mathrm{cm}^{-3}\right] .$$

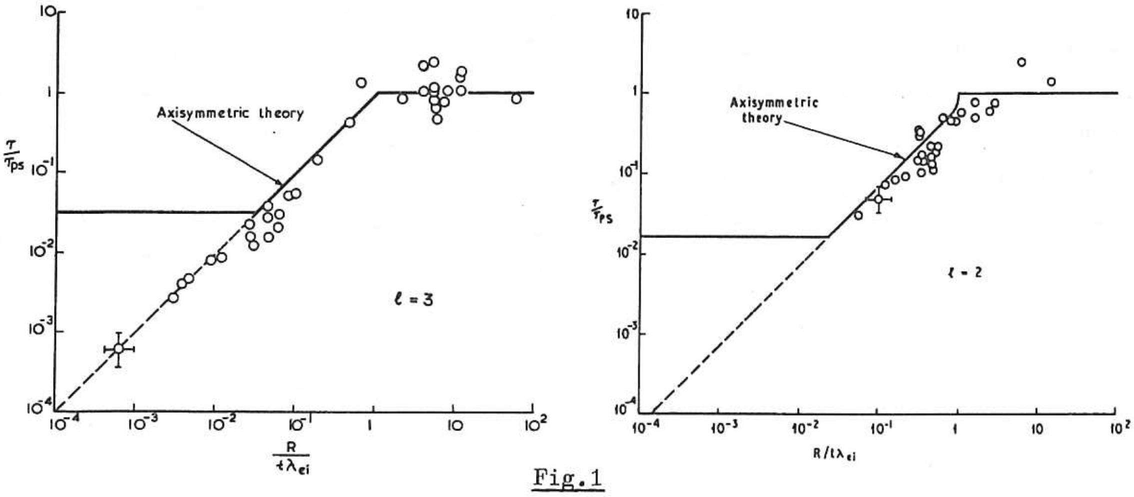

Fig.1

Normalized particle containment time as a function of the ratio of connection length to electron-ion mean free path for (a) $\ell = 3$ and (b) $\ell = 2$ experiments

The full lines in the figure are the predictions of theory for an axisymmetric system for the three regimes, collisional, plateau and banana. In the case of the plateau regime the line includes the effect of having $\rho_i\theta/r_n > 1$. Typical values of this ratio lie in the region 4–10 for PROTO-CLEO. The general effect is to increase the diffusion coefficient as $D/D_{plat} \to 2\text{–}3$ (10).

It is seen from the figure that there is good agreement between theory and experiment except in the banana region. There are two possible explanations for this :-

(1) Banana theory assumes $\rho_i\theta/r_n \ll 1$. Where this is not true the theory may not be applicable. It is considered that the general effect of $\rho_i\theta/r_n > 1$ may be to extend the plateau into the banana region (11).

(2) At these low values of collision frequency. we expect stellarator effects, (super bananas) to become important.

Using Gibson and Mason's routine (12) we have computed these effects and shown them to extend the plateau region in the way indicated by the broken line.

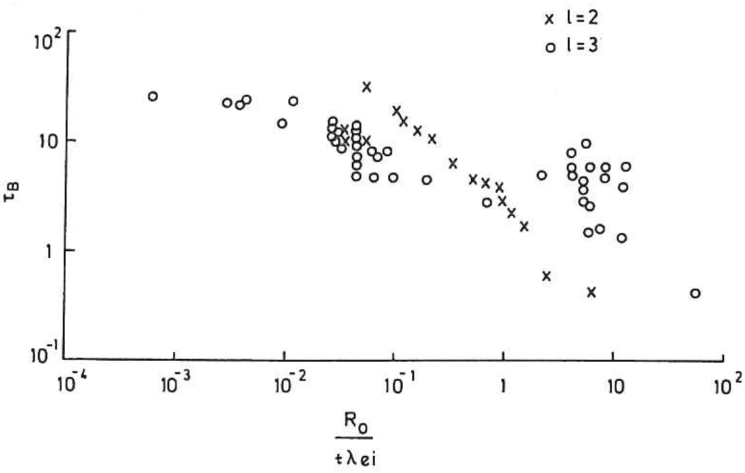

Fig.2

Particle containment time normalized to Bohm time as a function of the ratio of connection length to electron-ion mean free path for the results of Fig.1

In the case of the $\ell = 2$ measurements the diffusion coefficient has been assumed independent of radius and the value of t used is that appropriate to the magnetic axis. No measurements have been made in the weakly collisional regime for this case.

Figure 2 shows the ratio τ/τ_B plotted as a function of $R/t\lambda_{ei}$ where τ_B is defined as :-

$$\tau_B = 2.7 \times 10^{-8} \frac{a^2 B}{T_e} \quad \left[\text{cm, gauss, eV, sec}\right],$$

a is defined as the mean plasma radius, since the magnetic surfaces are not circular. This definition is given here because many different definitions of Bohm containment time appear to be in current use.

It will be seen that τ/τ_B decreases with increasing $R/t\lambda_{ei}$ for both $\ell = 2$ and $\ell = 3$ from a maximum value of ~ 20–30. Most of the collisional results show a containment of only about τ_B. Thus it appears unlikely that a Bohm-like scaling fits the results unless the character of density fluctuations (for example) changes dramatically as $R/t\lambda_{ei}$ is changed. This is discussed further in section 6.

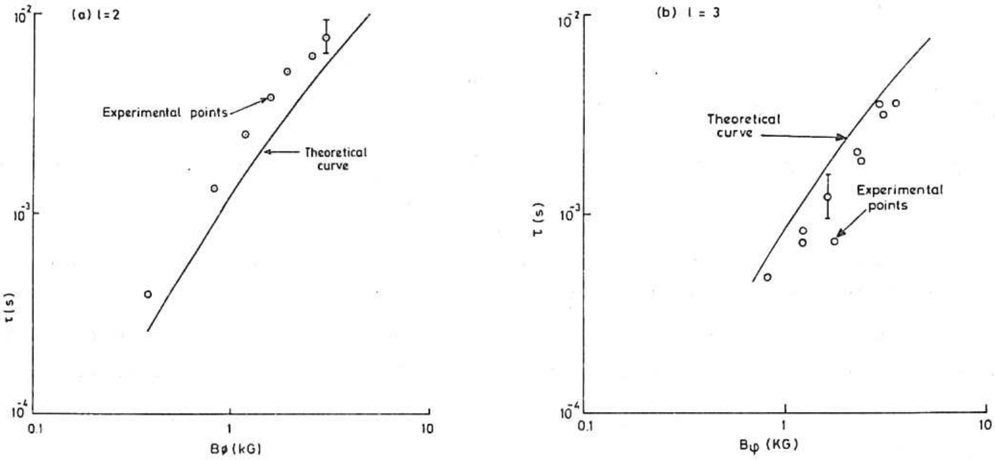

Fig.3

Containment time as a function of confining field B_φ for (a) $\ell = 2$ and (b) 7 field period $\ell = 3$ windings. The helical winding current I_ℓ is adjusted so that B_φ/I_ℓ is constant. The experimental points are compared with the predictions of plateau theory with the parameters, $T_e = 4$ eV, $n_e = 5 \times 10^{10}$ cm^{-3}, $T_i \propto B_\varphi$ and (a) $t = 0.35$ and (b) $t_{max} = 0.6$

Further evidence for non-Bohm-like behaviour is given by the scaling of confinement time with magnetic field. This is shown in Fig.3 where the experimental points are compared with a theoretical line calculated on the same basis as before. It will be seen that the law followed is $\tau \propto B_\varphi^n$ where n lies in the range $1.5 \le n \le 2$. This departure from a B^2 dependence can be argued as due to the dependence of T_i on B_φ, and has been allowed for in drawing the theoretical line.

Evidence for the dependence of containment time on the radius and t is difficult to obtain unambiguously, since variation of helical winding current changes t and the separatrix radius together. Results of the variation of helical winding current at constant B_φ for the $\ell = 3$ case are shown in Fig.4, in which containment time is plotted against the computed values of ta^2 for a given value of I_ℓ.

Also shown in the figure are two theoretical lines. One is the straightforward prediction for an axisymmetric system. The other takes account of the reduction in containment time due to particles trapped by the helical field. This may be important, particularly in the case of the 13 field period winding

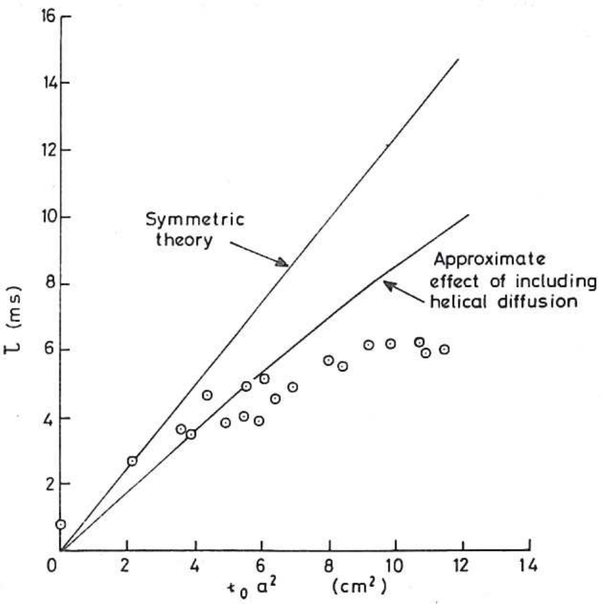

Fig.4

Containment time as a function of t_0a^2 for the 7 field period $\ell = 3$ winding, with experimental parameters $B_\varphi = 3.8$ kG and $\sim 3 \times 10^{10}$ cm^{-3}. The experimental points are compared with (a) symmetric theory and (b) theory including diffusion due to helically trapped particles for which the variations in helical field strength at the separatrix are comparable with the variation due to toroidicity. The results are somewhat unconvincing since the increase of τ is not as rapid as expected. It is conceivable that the magnetic surfaces are less perfect at higher values of t. For the $\ell = 2$ case the containment time τ/a^2 normalized to unit radius, is plotted as a function of t in Fig.5. The results lie in both collisional and plateau regions. For small values of rotational transform equilibrium may be preserved by some effect other than the helical windings (it is certainly the case that at zero transform the containment time is still some 0.3 msec). At large values of t the containment time is shorter than theory predicts, but the general agreement is better than for $\ell = 3$.

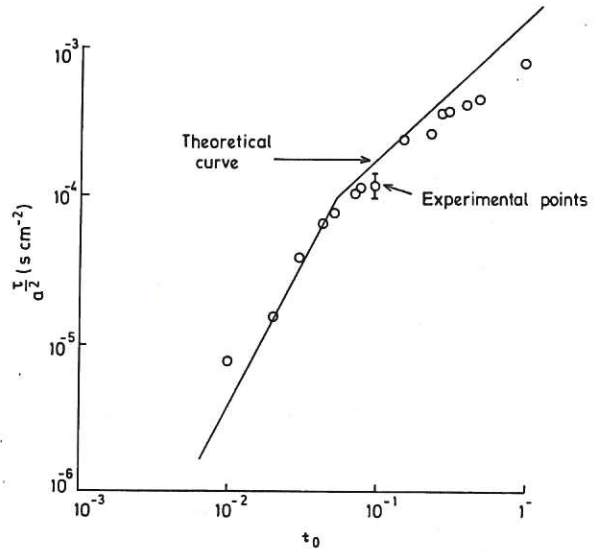

Fig.5

The ratio τ/a^2 as a function of the central value t_0 for the $\ell = 2$ winding, with experimental parameters $B_\varphi = 3$ kG, $T_e = 2.5$ eV and $n = 6 \times 10^{10}$ cm^{-3}. The experimental points lie in the plateau and collisional regimes and are compared with the relevant theoretical curve

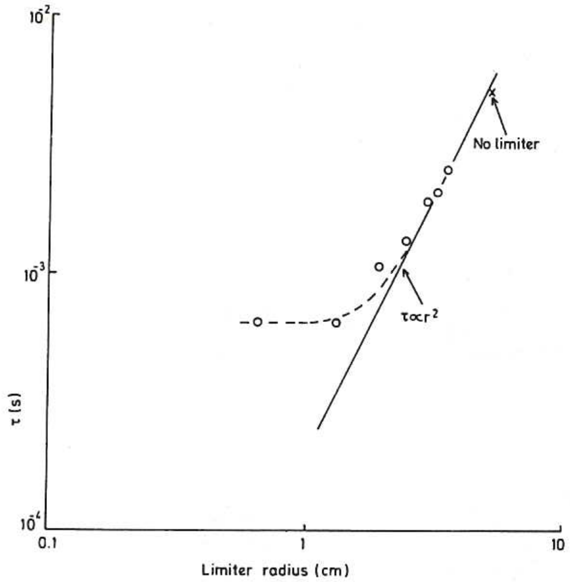

Fig.6

Containment time as a function of effective plasma radius, as determined by a limiter for the $\ell = 2$ winding

The use of an adjustable limiter has enabled the variation of τ with plasma radius to be further explored. The rather crude results available from this are plotted in Fig.6. It is seen that the variation is asymptotic towards an r^2 fit but there is a departure at smaller radii, where the action of the limiter is suspect. Again the containment time does not fall below about 600 μs, no matter how small the limiter radius.

The significance of these results as far as the effect of shear is concerned should be noted. Since for $\ell = 2$ the shear is mainly near the plasma edge a limiter should produce a relatively shear-free plasma. However, the value of τ measured does not fall off at a rate greater than r^2, indicating that containment for $\ell = 2$ without shear is still possible. In this the results agree with those of reference (21), again a case with little shear. The results of Fig.6 were obtained in a condition of non-resonance and we have no evidence for the effect of a degenerate rotational transform on this case.

5. DENSITY AND POTENTIAL CONTOURS

The ion density and floating potential have been sampled over the whole region inside the separatrix using a three pin rotatable probe. Results are given for $\ell = 3$ in Fig.7 and $\ell = 2$ in Fig.8 at several times after firing the gun. In all cases the computed position of the separatrix is also shown. These results are made on a one shot basis and since the separate shots are not reproducible to better than $\pm 50\%$ the probe saturation current is normalized using the interferometer reading (of density over a line of sight) to a particular value of initial density. The floating potential plots are not normalized. Smoothed contours are then drawn through the experimental points.

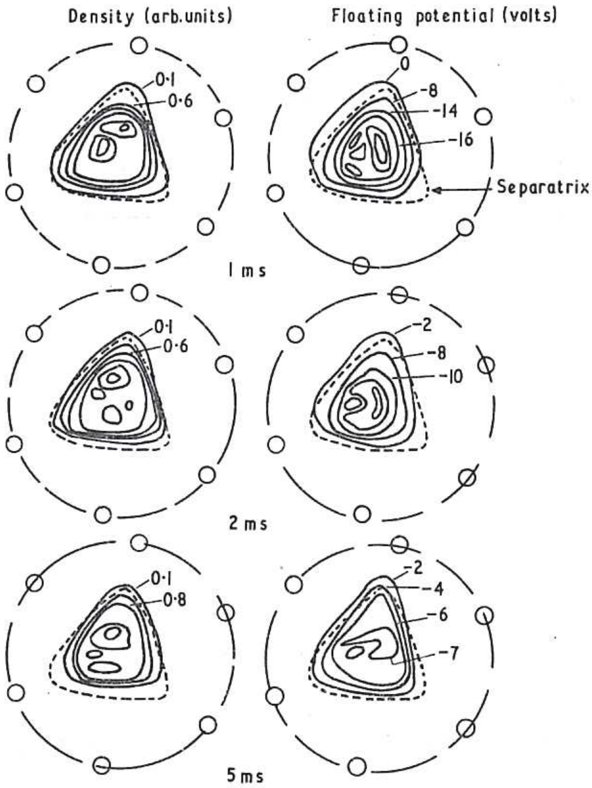

Fig.7
Distribution over a minor cross section of (a) density, (b) floating potential, at times 1, 2, and 5 ms after plasma injection, for the 7 field period $\ell = 3$ winding. Potential distributions are in volts. Density scale is arbitrary, but initial central density is $\sim 5 \times 10^{10}$ cm^{-3}. Also shown by the broken line is the computed separatrix for the conditions $B_\varphi = 3$ kG, $t_0 = 0.6$. The enclosing circle represents the helical winding radius

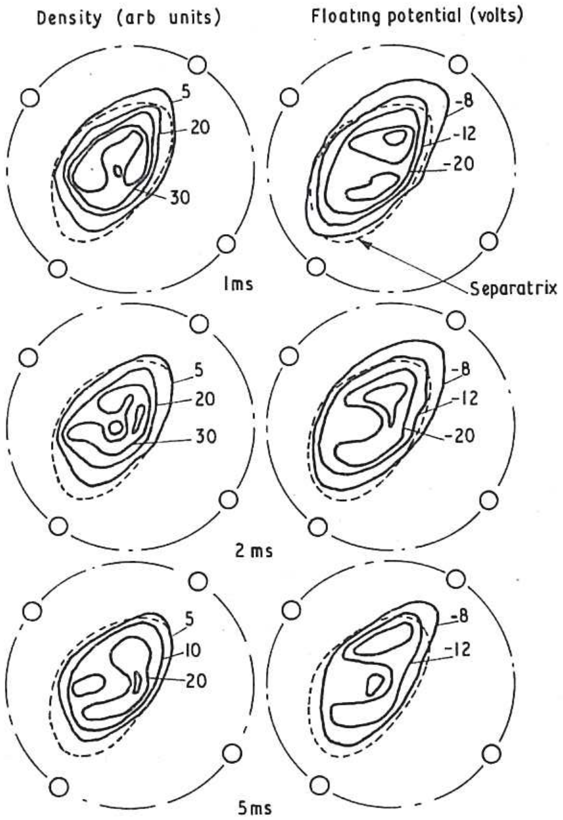

Fig.8
A distribution similar to Fig.7 but for the $\ell = 2$ winding. Initial central density $\sim 5 \times 10^{10}$ cm^{-3} and separatrix computed for the condition $B_\varphi = 3$ kG, $t_0 = 0.35$

It is seen that in both $\ell = 2$ and $\ell = 3$ there is reasonable agreement between the density and potential contours and magnetic surfaces in the outer regions of the plasma.

On the inside, however, there appears to be a lack of coherence. This may possibly be due to the filling method and the lack of shot-to-shot reproducibility of the plasma. There is no guarantee that standardizing the interferometer reading is the complete answer to unreproducibility.

It is known that no strong T_e variation exists and thus floating potential contours are expected to be equivalent to plasma potential surfaces. Assuming these to be orthogonal to the direction of electric field, a diffusion flux can in principle be determined. Fig.9 shows contours near the separatrix superposed on a magnetic surface with the errors of the experiment indicated. These errors are so large that the results of such a flux calculation are not meaningful, (in particular a small difference of character between V_f and V_p would make a large difference to the flux) and thus it is possible only to state qualitatively that because of the good agreement between the contours of n, V_f and magnetic surfaces, that we believe convection not to play an important part in plasma loss. It should be noted in particular, that the errors are too large to resolve the small charge separation potentials given by neo-classical theory for the plateau region.

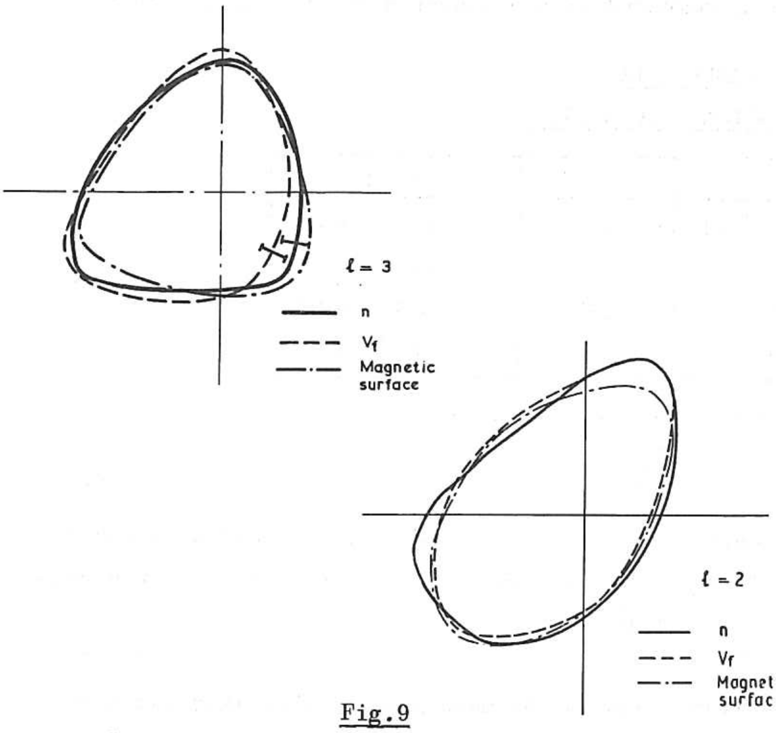

Fig.9

Contours of density and floating potential near the plasma edge, superposed on a magnetic surface for (a) $\ell = 3$ and (b) $\ell = 2$ experiments

6. FLUCTUATION MEASUREMENTS

The use of multi-pin probes has enabled fluctuations $\tilde{n}$, $\tilde{E}_\theta$, $\tilde{E}_\varphi$, and $\tilde{V}_f$ to be measured as a function of radius in the minor cross section. Typical results are shown in Fig.10 in which r m s value of the fluctuation are shown. It is seen that for both $\ell = 2$ and $\ell = 3$ there is a peak of $\tilde{E}_\theta$ and $\tilde{n}$ in the region of decreasing density at the edge of the plasma. The graph of $n_o(r)$ has a hole in the centre - this is possibly due to the drain of particles by the probe at small radii. (N.B. it is also seen on the contour plots of the previous paragraph.) For these particular results measurements of the time averaged cross correlation $\langle E_\theta(\tau)\tilde{n}(\tau)\rangle$ have been made. The results for the radii at which the fluctuations are a maximum are shown in Table III. From these can be evaluated a radial flux $\langle\tilde{E}_\theta\tilde{n}\rangle B_\varphi^{-1}$. Some measurements have been made of the way in which these fluction levels vary over a magnetic surface,

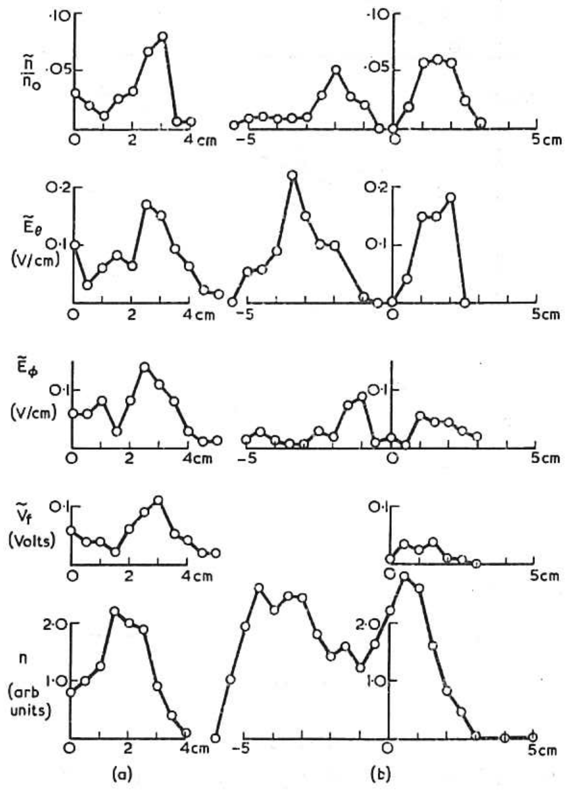

Fig.10

Radial profiles of fluctuations measured in (a) $\ell = 3$ and (b) $\ell = 2$ experiments and it has been shown that there is no place at which the flux will exceed this value indicated. Thus a containment time may be calculated from these results. The values obtained are 0.4 s ($\ell = 3$) and 0.15 s ($\ell = 2$) compared with a measured ~5 ms, i.e. both too long to explain the observed loss.

TABLE III

FLUCTUATIONS CORRELATION

	$\ell = 3$	$\ell = 2$	
Radius of measurement (cm)	3.0	+ 1.5	- 4.5
$\tilde{E}_\theta$ (V/cm)	0.1	0.69	0.024
$\tilde{n}/n_o$ (n_o = local density)	0.036	0.048	0.016
Correlation coefficient α	0.05	0.15	0.15

It has been pointed out[13] that while the expression is:-

$$\Gamma_r = \frac{\langle \tilde{E}_\theta \tilde{n} \rangle}{B_z} \qquad \dots (1)$$

represents the radial flux due to fluctuations truly in a straight system, momentum considerations demand that in a toroidal system one should rather take the components given by:-

$$\Gamma_r = \frac{\langle \tilde{E}_\varphi \tilde{n} \rangle}{B_\theta} \qquad \dots (2)$$

since $B_\theta \ll B_\varphi$, unless $E_\varphi \ll E_\theta$ the resultant loss may be much greater than that given by expression (1). It will be seen from Fig.10 that $\tilde{E}_\varphi$ is not much less that $\tilde{E}_\theta$.

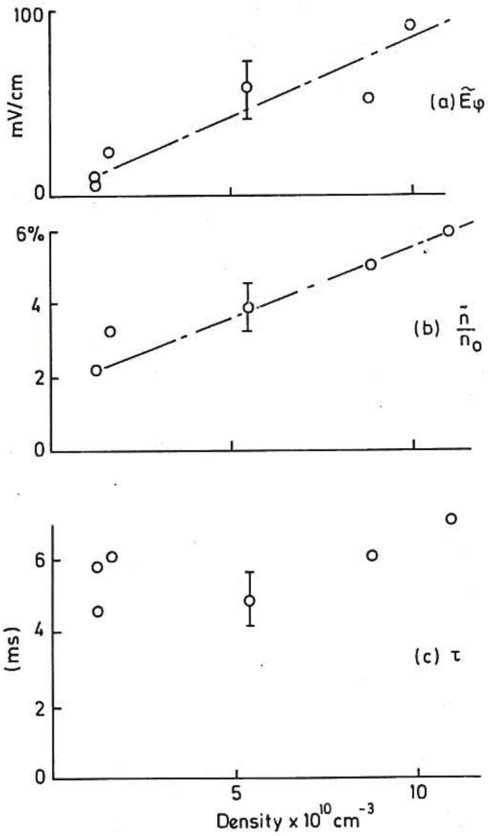

Fig.11

Variations of (a) $\tilde{E}_\varphi$, (b) $\tilde{n}$ and (c) containment time with average plasma density. $\tilde{E}_\varphi$ and $\tilde{n}$ are measured for the radius at which the fluctuations are a maximum

We have measured the r m s value of $\tilde{n}$ and $\tilde{E}_\varphi$ as a function of density for the $\ell = 2$ machine, and these results are plotted in Fig.11. This also shows the density decay time measured by microwave interferometer. It is seen that both $\tilde{n}$ and $\tilde{E}_\varphi$ increase with increasing density but that τ remains substantially constant. The cross correlation coefficient for $\langle n E_\varphi \rangle$ varies from an insignificant value at lowest density to a value of 0.51 at the highest density. Again the variation of $\tilde{E}_\varphi$ and $\tilde{n}$ around a magnetic surface, measured at the highest density used, shows no point at which the fluctuation level is increased over these values shown.

The correlation between $\tilde{n}$ and $\tilde{E}_\varphi$ is however such as to give a flux $\langle \tilde{E}_\varphi \tilde{n} \rangle_{\theta,t} B_\theta^{-1}$ directed towards the centre of the minor cross section. This in association with the dissimilarity in density dependence, between $\tilde{E}_\varphi$ $\tilde{n}$ and τ, suggests that these fluctuations cannot play a dominant part in the plasma loss mechanism.

By taking the relative values of $\tilde{V}_f$ and $\tilde{E}$ we can crudely estimate the magnitude of wavelength of the fluctuations. By so doing we arrive at the conclusion that $k_{\perp} \sim k_{\parallel} \sim 1\ cm^{-1}$. Furthermore we see that the frequency lies in the range 10–100 kHz, typically ~ 30 kHz. Thus the phase velocity of the wave is typically of the order of 2×10^5 cm/s. This is to be compared with ion thermal velocities of $\sim 5 \times 10^6$ cm/s and thus represents a very slow wave which ought to suffer strong Landau damping on the ions.

One obvious solution is that the fluctuations are introduced by the probe itself and are not a function of the plasma. This is very difficult to check, but we have made measurements with another probe in close proximity to the measuring probe, without any obvious change in the character of the fluctuations.

7. MEASUREMENT OF CONDUCTIVITY

The plasma impedance, and hence electron temperature, has been determined by a method used by the Princeton group[14], in which two Rogowsky coils encircle the minor circumference of the plasma. One coil is energised by an audio oscillator and the resulting current of a few amperes in the plasma is determined by the EMF induced in the second coil. These coils were positioned inside the vacuum vessel within the helical winding, but outside the separatrix. They were wound very uniformly to minimize end errors which encourage stray signals to be picked up from the high pulsed currents flowing in the neighbouring helical conductors.

The plasma conductivity was determined over a wide range of frequency. In the results given below a frequency of the applied signal of 6.5 kHz was used since this gave adequate power transfer from coil to plasma, small inductive reactance of the plasma by comparison with its resistive component and negligible skin effect in the plasma. Fig.12 shows the ratio of the measured conductivity to the Spitzer conductivity as a function of $R/t\lambda_{ei}$. In this the Spitzer conductivity is determined from double probe measurements of electron temperature. Shown as a full line is the calculated value obtained from the theory of Galeev[15]. There is a tendency for the ratio of $\sigma_{\parallel}/\sigma_{\perp}^{0}$ to fall with decreasing $R/t\lambda_{ei}$ as predicted theoretically, although the spread of the measurements is too large to be certain of this fact. The agreement between theory and experiment is as good as can be expected, taking into account that this conductivity is an average value across the plasma column. We conclude that there is no anomalously high plasma resistance.

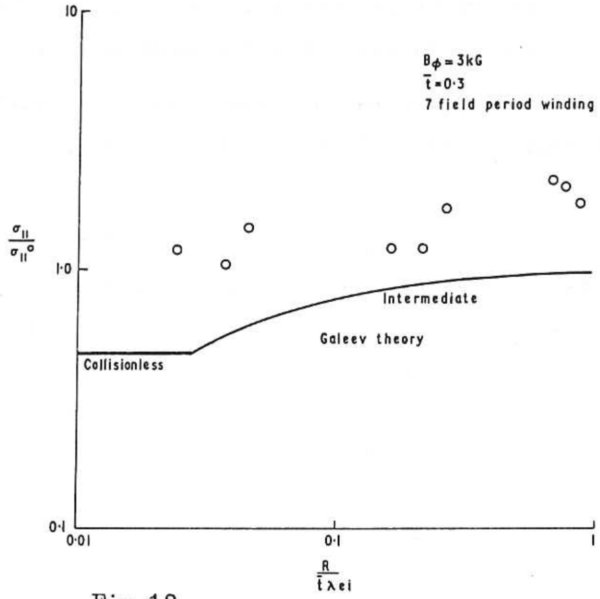

Fig.12
Experimental points and theoretical curve for the variation of the ratio of the plasma conductivity to Spitzer conductivity with the ratio of connection length to electron-ion mean free path

8. DIFFUSION DRIVEN CURRENT

It has been pointed out be several authors[15-17] that diffusion in a weakly collisional axisymmetric toroidal plasma should be accompanied by a current flow parallel to the magnetic field. Galeev[15] and Stringer[18] have shown that this current should also exist in the plateau regime. If the theory is applicable to systems which have no axisymmetry it should equally exist in a gun-injected stellarator, in which the absence of ohmic heating should make its detection easier. The predicted level of the current for PROTO-CLEO, taking into account the measured diffusion coefficient and density gradient, is about 1 - 5 A. To study such currents in the presence of the neighbouring helical winding currents requires careful measurement.

Three methods of measurement have been used :-

(1) Using one of the Rogowsky coils made for the conductivity measurement. This is wound very uniformly with a minimal end error and was surrounded by a copper electrostatic screen to avoid stray pick-up. A single turn loop co-planar with the coil allowed backing off not only the single turn B_φ pick-up of the Rogowsky coil but also the residual signal due to end errors.

(2) Using the helical winding as the secondary of an air-cored transformer with the current carrying plasma as the primary. In this case the 15 kA carried by the helical winding has to be backed off and in addition the helical winding links the B_φ so this must be backed off also.

(3) In the course of the transit time magnetic pumping experiments it proved necessary to install an electrostatic screen, a Faraday cage, between the helical winding and plasma. This effectively constitutes a wire torus with a break so that it is not a short circuited turn. This was used as a detector of diffusion driven current in the same way as the helical winding, with the considerable advantage that it did not have 15 kA flowing through it. By this method a small signal was seen at the time of injection, but this is thought to be a property of the injection process since it decays to zero in a few hundred microseconds.

In no case can any signal be seen which can be attributed to the diffusion driven current. The limit of measurement is about 100 times below the value of the expected current.

Further evidence of directed fluxes has been sought by the use of a 'Janus' probe[19]. This consists of two equal area single probes spaced 7 mm apart and each surrounded by a cylindrical screening electrode of outside diameter 2 mm. so that each probe could collect particles over only a small angle of incidence, either upstream or downstream. By suitably biassing the probes to collect either electrons or ions and balancing the signals from them, a measure of the directed flux can be obtained. The difference in the floating potential of the two probes was also used as an indication of a directed flux of ions.

The results, although relatively crude, appeared to show that no directed velocity greater than about one tenth of the ion thermal velocity exists in the PROTO-CLEO plasma. Thus there is no sign of the 'catherine wheel' effect noted by the Lebedev group[20].

9. DISCUSSION OF RESULTS

The results presented here show that in the absence of a limiter, both $\ell = 2$ and $\ell = 3$ systems exhibit the same sort of plasma behaviour. There is still considerable shear at the separatrix for $\ell = 2$ which is comparable with $\ell = 3$.

This may account for the absence of any definite minimum in containment time at integral values of ι such as are found in other experiments[21,22].

In both cases there are fluctuations characterized by slow waves, clearly not having the character of drift oscillations, although they are localised in regions of steepest density gradient. Since, as Stringer[23] has pointed out, resonant particle diffusion in the plateau region gives rise to a loss band in velocity space, it is possible that these fluctuations are associated with this, which may explain their short wavelength along the magnetic field. As has been noted above, they do not seem to be associated in any obvious way with the plasma loss mechanism.

It has been shown in Fig.1 that plasma can be contained in both $\ell = 2$ and $\ell = 3$ systems, for a time differing from that calculated on the basis of collisional diffusion by less than a factor of 2. However, the small current existing as a consequence of this diffusion does not appear to exist.

Stringer[18] has shown that the φ component of the particle force equation can give a physical insight into the mechanism of plasma diffusion in a symmetric toroidal system. Bickerton[13] has drawn attention to the effect of fluctuating density and electric field on this equation. Ignoring inertial terms he derives the following result for the low density regime in a symmetric system :-

$$-B_0 \Theta \Gamma_s = \eta n_0 j_0 + \eta \langle \tilde{n} \tilde{j} \rangle_{\theta,t} + \langle \tilde{n} \tilde{E}_\varphi \rangle_{\theta,t} \qquad \ldots (3)$$

where the fluctuating quantities are represented by a tilda and j_0 is the diffusion driven, unidirectional current. The averaging must be carried out over a magnetic surface as well as over time. It is, in theory, possible to fold measured values into this equation to assess the importance of each term on the momentum balance. The term $\langle \tilde{n} \tilde{j} \rangle$ must generally be small, so that in the absence of diffusion driven current the diffusion flux Γ_s must be balanced entirely by a flux determined from the correlation of $\tilde{n}$ and $\tilde{E}_\varphi$. This, in fact, is the basis of equation (2) above. We have already seen that this flux cannot provide such a balance, either in magnitude or direction, and it thus appears difficult to satisfy equation (3). Some reasons for this may be as follows :-

(1) As we have said above, it is possible to discredit the fluctuation measurements on the grounds that the effects may be introduced by the measuring probe. This does not seem likely although there is the question of probe cleanliness. Chemical cleaning of the surface is used, but discharge cleaning is not practical in our system. We use as our criterion that we believe the probe to be clean when the floating potential is the same, whether measured by (a) that potential where a low impedance probe drawns no current to ground, or (b) that potential which a high impedance probe will take up with respect to ground.

(2) It has been pointed out[24] that for the stellarator case, all terms in equation (3) must be averaged over a volume, since axial symmetry does not exist. The argument is analogous to that which gives the rotational transform. The most likely procedure therefore is to average $\langle \tilde{n} \tilde{E}_\varphi \rangle B_\theta^{-1}$ over a period of the helical field rather than over a magnetic surface as here. It is, though, difficult to see that this could make a marked difference to the behaviour unless loss band diffusion is occurring.

(3) We have assumed that the value of $\langle \tilde{n} \tilde{j} \rangle$ must be small, i.e. that the fluctuating electric field is balanced by some other effect, e.g. pressure gradient. It is possible that the effective resistivity could be greatly enhanced, although the quasi d c measurements show a value of η_0 close to the classical one.

(4) Equation (3) ignores the inertial terms and considers only the equilibrium situation. It is possible that this may not exist in the PROTO-CLEO experiment since τ_{ii} is comparable with the time of measurement. Theoretically, however, it is expected that the build up of an equilibrium condition should take place in times shorter than this.

(5) The existence of a loss band in velocity space for the ions could conceivably have an effect on the existence of the diffusion driven current. However, no such loss band exists for the electrons and an equation of the form of (3) must be satisfied independently for both species.

(6) It is doubtfully possible that the fluctuation terms $\langle \tilde{n} \tilde{E}_{\varphi} \rangle$ could be balanced by some other large term which does not appear in the equation.

(7) It is possible that field lines are not properly closed. However, measurements with an electron beam do not support this view. Further, contours of n and V_f agree well with the magnetic surfaces.

(8) It is conceivable that a convective cell extending to the φ direction could provide large quasi d c terms not included in equation (3), i.e. this equation is being pushed too far to be consistent with the accuracy of the measurements.

10. CONCLUSIONS

This work is less than conclusive in its results. It has been satisfactorily demonstrated that plasma injected into a high shear, truly toroidal stellarator can be contained for times as long as predicted on the basis of collisional diffusion, and that decay proceeds smoothly without any large fluctuations of electric field or plasma density. At very low collision frequencies, effects are observed which could possibly be due to differences between a symmetrical system and a stellarator.

It has, however, not been possible to find any evidence of diffusion driven current. It is expected that this current should exist in a stellarator, at any rate where the collision frequency is high enough so that helically trapped particles are not important(24); although one author disagrees with this(25).

Thus it is not possible to say conclusively that the loss of plasma from the PROTO-CLEO stellarator is solely by collisional diffusion. However, the results are sufficiently encouraging for the future of larger, ohmic heated stellarators.

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