CLM-P 185

This document is intended for publication in a journal, and is made available on the understanding that extracts or references will not be published prior to publication of the original, without the consent of the authors.

United Kingdom Atomic Energy Authority

RESEARCH GROUP

Preprint

A STUDY OF THE DIFFUSION OF HIGH-β PLASMA IN A THETA PINCH

H. A. B. BODIN
A. A. NEWTON

Culham Laboratory
Abingdon Berkshire

1969

UNCLASSIFIED
(Approved for Publication)

CLM - P 185

A STUDY OF THE DIFFUSION OF HIGH-β PLASMA IN A THETA PINCH

by

H.A.B. BODIN
A.A. NEWTON*

(Submitted for publication in Physics of Fluids)

ABSTRACT

This paper describes a direct measurement of the perpendicular diffusion coefficient in a theta pinch operating in the low pressure regime with zero bias field. The diffusion was studied by comparing the measured time variation of the radial electron density distribution with computations assuming classical and other resistivities. A coil 8 metres long is used in order to delay end effects and measurements confirm theoretical predictions that the plasma in the mid-plane is uninfluenced by the ends and free of energy losses for about 25 μsec.

The plasma temperature was varied from 90-160 eV and the values of density and beta on the axis are 3-4 × 10^{16} cc^{-1} and 0·7 respectively. In the early stages (before 2 μsec) diffusion at approximately the Bohm rate is found, and this is belived to be due to a streaming mechanism. At later times the measured diffusion coefficient is in good agreement with the classical value in all conditions studied, and the experimental error is such that diffusion is unlikely to exceed 1/10 of the Bohm rate.

* On leave of absence at Los Alamos Scientific Laboratory, Los Alamos, New Mexico, U.S.A.

U.K.A.E.A. Research Group,
Culham Laboratory,
Abingdon,
Berks.

January, 1969(SLW)

C O N T E N T S

1. INTRODUCTION

The theta pinch has been studied for many years and when operating in the low pressure regime with zero bias field a plasma with a temperature in the range 100 eV to 1 keV at a density between 10^{16} and 10^{17} electrons per cc can be produced[1-4]; beta usually lies between 0·4 and 0·9. Experimental work has been reported on the problems of heating and energy loss[5], including particle flow from the ends[3]. There have also been investigations of the hydromagnetic stability[6,7], but until recently no work has been reported on the perpendicular diffusion, a subject studied extensively in low beta toroidal systems. For example, in many stellarator experiments[8] the confinement time was consistent with an outward diffusion at the Bohm[9] rate rather than the classical rate[10] due to binary collisions.

A study of diffusion in the theta pinch is of interest because, firstly, the potentialities of this device for containing a hot plasma for long times depends upon the diffusion rate. Secondly, it is theoretically possible (see for example, ref.11) that some micro-instabilities which can cause enhanced diffusion in a low beta plasma are damped at high beta. Furthermore, using the method described below the diffusion coefficient can be determined directly when the plasma is well isolated from the walls.

In most theta pinch experiments a direct measurement of the diffusion coefficient has not been possible because the radial density distributions are influenced by end effects such as particle losses and thermal conduction[5] so that changes in the profile due to radial diffusion cannot be identified. Indirect estimates of the diffusion coefficient have been made for reversed field discharged by comparing the measured end loss rate with theoretical models based on axial flow, and on radial diffusion followed by axial flow[12,13]. There is no general agreement between these indirect estimates; in some experiments the results indicated anomalous diffusion[13] while in others classical diffusion gave best agreement[12]. In an experiment with zero bias field an attempt was made to separate diffusion from other processes influencing the density distribution by analysing the data in terms of the trapped flux[14]; there was some indication of anomalous diffusion just before the plasma became unstable but the accumulated errors were large.

In the early stages (first 2 μsec) of discharges operating in the low pressure regime there is better agreement on diffusion between different experiments. Indirect evidence for anomalous diffusion has been obtained from the shape of the density distributions[3,4,14,15] which indicated a diffuse current sheath and an average beta much less than that predicted by MHD theory[16] using the Spitzer[10] resistivity. The measured beta on the axis after 1 or 2 μsec was often about 0·8, instead of the predicted value of unity, a further indication of non-classical diffusion at early times.

In this paper a direct measurement of the diffusion coefficient in a theta pinch operating in the low pressure regime is described, made in conditions where the density distribution is uninfluenced by energy and particle losses for times long enough to measure diffusion rates of one-tenth of the Bohm value (the Bohm time[8] is in the range 5-10 μsec). The principle of the method is to compare the time variation of the radial density distribution with the results of computations using the Hain-Roberts[16] MHD code assuming classical and other resistivities.

In order to reduce axial losses the coil length has been increased to 8 metres, and it has been shown both theoretically and experimentally that the plasma in the mid-plane is unaffected by particle or energy losses for about 25 μsec; the thermal conduction cooling time is several hundred microseconds. The impurity concentration is between ½ and ¾% of oxygen and so radiation loss is also negligible. The use of a coil 8 metres long on the megajoule bank gives a peak magnetic field in the range 20-25 kG and electron temperatures in the range 100-160 eV at densities of about 3-4 × 10^{16} cc^{-1} on the axis. The plasma, whose maximum beta is about 0·7, is collision dominated.

This paper enlarges on some preliminary measurements[17] and presents new results. Following a description of the experimental apparatus and the method of measurement the results on the diffusion are presented. Diffusion in the early stages is discussed and best agreement between theory and experiment is obtained with an artificial resistivity chosen to give the perpendicular diffusion coefficient the Bohm magnitude and scaling. After the first 1 or 2 μsec no further anomalous diffusion is detected and the observations agree with classical theory.

2. EXPERIMENTAL APPARATUS AND METHOD OF MEASUREMENT

The experiments were carried out on the Culham 1 megajoule capacitor bank[18] feeding a coil 771 cm long and 11 cm bore. The 950 cm long quartz discharge tube was 9·5 cm O.D. and 8·3 cm I.D. Electrical parameters of the experiment are shown in Table I. The variable added inductance shown in the left-hand column (normally 4·3 nH) is included in the circuit to give a longer decay time and a smaller peak to peak ripple when the crowbar, comprising 32 solid dielectric switches, is used. Peak fields at 30, 34 and 40 kV were 18, 20 and 24 kG, and were reached in 5·5 μsec; when crowbarred, the field decayed with a time constant of 160 μsec, as shown in the oscillogram trace in Fig.1. The coil was the same length as the cable termination strip and consequently parallel current flow is to be expected everywhere along the coil except close to the ends.

Deuterium at a filling pressure of 20 mtorr was used and the gas was preionized by an axial current pulse[20] generated by a 0·4 μF capacitor charged to 40 kV. This current reached a maximum value of 8 kA and was short-circuited at its second zero. About 130 J were dissipated in the gas, producing more than 50% ionization.

Method of Measurement

The radial distribution of the electron temperature was measured by the standard 90^{o} Thomson scattering technique using a 12 channel spectrophotometer[21]. The use of this instrument to measure the electron temperature in the present experiment and a discussion of the results obtained, is reported elesewhere[22]. Its spatial resolution was about 1 mm in the direction perpendicular to the plasma axis.

An independent value of the average temperature was obtained from the diamagnetic loop[23] signal, analysed in conjunction with the density distribution[24]. The principle of this method is best understood by assuming a model in which the plasma is a uniform cylinder of radius r. The diamagnetic signal, S, is then given by

$$SB = 8\pi\ k\ N(T_e + T_i)\ f(\beta)$$

where the line density $N = \pi r^2 n_e$, $f(\beta)$ varies slowly with β and lies between 1 and 2, and the other symbols have their usual meanings. In practice, since both β and n_e are functions of radius the diamagnetic signal is an integral over the observed radial density distribution.

The relative density distribution was determined by three different techniques: by Thomson scattering using the spectrophotometer[21,22], and from the emitted radiation in the visible spectrum, which was spatially resolved both by means of a 10 channel fibre bundle assembly[25] and with a calibrated image convertor camera. In the last two methods the data was unfolded by means of an Abel inversion and the absolute value of density was obtained by equating the integrated profile to the line density determined from the mass oscillations[26]; at a filling pressure of 20 mtorr the line density was equal to the initial gas filling to within the experimental error of 20%.

In the fibre bundle technique a line-free region of the spectrum 10 Å wide at 4978 Å was selected using an interference filter and the plasma light in this wavelength interval spatially resolved into 10 channels. This method is unaffected by the line radiation from the plasma or by stray light.

The calibrated camera gives a superior spatial resolution (equivalent to 40 channels) but collects light over the whole spectral range detected by the S 11 photocathode (3000–6500 Å). Thus the result can be affected by line radiation, and in obtaining distributions it must be assumed that the impurity ions (if any) are homogeneously distributed in the plasma. The camera was calibrated immediately prior to the discharge using the same electron optics as used for viewing the plasma with a 20 step wedge and a tungsten flash light. The image of the wedge is recorded on each piece of cut film, beside the area about to record plasma light. Care was taken to investigate the spatial uniformity of the camera sensitivity and to operate in its region of linear response. The film and calibration are micro-densitometered together and the radial density distribution is obtained by means of an Abel inversion. Background light in this method was reduced to about 2% of the peak of the intensity distribution by grinding the inner tube surfaces and blackening the outside opposite the viewing port. The distributions obtained by the three techniques are shown in Fig.2, and are seen to agree within the experimental error. The scatter between the points is greatest for the laser technique, where each point represents one discharge. This agreement justified the various assumptions about background light and impurities which affect each method differently. The calibrated camera was used to obtain all the density distributions analysed in this paper.

The radial temperature distribution is also shown in Fig.2, and it is seen that the temperature is approximately constant over most of the plasma, as expected theoretically.

3. PLASMA PROPERTIES

The diffusion was studied at three values of the bank voltage: 30, 34 and 40 kV; the measured values of temperature and density are shown in Table II. It is seen that the peak density is 3–4 $\times$ 10^{16} electrons cc^{-1} while the electron temperature is in the range 90 to 160 eV; beta on the axis is about 0·7. In Table III the plasma parameters calculated from the measured density and electron temperature, assuming $T_e = T_i$, are given for a discharge at 120 eV; the values in the other conditions are of the same order. It is seen that the plasma is collision-dominated, the electrons and the ions are in equilibrium, and the mean path is comparable with the radius. The plasma radius is about 1–2 cm and contains some 10 ion Larmor radii. The ratio between the Bohm and classical diffusion rates is given approximately by $\omega_{ce}\,\tau_{ei}/16$, (see Section 4 and Appendix), which lies between 20 and 40 on the axis.

The time for which the radial density distribution in the mid-plane is undisturbed by end effects has been calculated. With a sound speed of 10^7 cm sec^{-1} the rarefaction wave propagating inwards from the ends[27] cannot reach the mid-plane for at least 40 μsec. The thermal conduction cooling time is several hundred microseconds. Experimentally, the line density was constant for at least 25 μsec and the time variation of the diamagnetic signal and electron temperature both agree with theoretical curves calculated using the uniform plasma model assuming adiabatic behaviour and no energy loss (see also ref.22). The results are summarised in Fig.3, which shows that within the experimental error the plasma is free of particle and energy losses for some 25 μsec. The decrease in the diamagnetic signal, first seen at about 22 μsec, is associated with the onset of the residual instability (see below) and is thus believed to be of hydromagnetic origin. The Alfven time, i.e. the time taken by a hydromagnetic disturbance propagating from the end to reach the mid-plane, and has a value of about 20 μsec;* and the mid-plane is predicted to be free from any hydromagnetic effects originating at the ends for this time.

The plasma remains stable and drift-free along its whole length for 25-30 μsec (at 34 kV), except for a small amplitude (< radius) lateral motion, similar to the wobble[4] but of much lower amplitude and smaller growth rate. At a later time the plasma is disturbed by an instability,[17] known as the residual instability, which is a mixture of $m = 1$ and $m = 2$ (one or other of these may predominate according to conditions). The onset time of this instability varies[17] as $\ell p/V^2$, where ℓ is the coil length, p the filling pressure and V the bank voltage. At 34 kV and 20 mtorr it appears at 25-30 μsec. Many of these features are seen in Fig.4, which shows a stereoscopic streak camera photograph taken in the mid-plane, and photographs at three other axial positions of the same discharge.

The results presented in the rest of this paper were all obtained before the onset of the residual instability.

4. PRINCIPLES OF THE METHOD FOR MEASURING DIFFUSION

The principle of the method of studying diffusion is to measure the radial electron density distribution as a function of time and compare this with theoretical predictions using the Hain-Roberts MHD code with classical and other resistivities (i.e. classical and other diffusion coefficients). The profile changes with time as the external magnetic field varies and this adiabatic variation is included in the computations. In order to make an approximate comparison between the results and the empirical Bohm coefficient

---

* V_A calculated from axial density and external field. For a more accurate value of this time the appropriate average value of V_A must be used; this is discussed in ref.28.

$D_B = 1/16\ ckT_e/eB$ the data are compared with computations assuming a "Bohm resistivity" η_B (and $\eta_B/10$), chosen so that when it replaces the Spitzer value, η, in the expression for the classical diffusion velocity $v_\perp = -\frac{\eta}{B^2}\nabla p$, (Ref.10, eq.(3.16)) a velocity with the Bohm scaling and magnitude results. The value used in this paper, which is deduced in the Appendix, is

$$\eta_B = \frac{\omega_{ce}\,\tau_{ei}}{16}\,\eta\ .$$

The diffusion studies may be conveniently divided into two phases of the discharge; firstly, up to two microseconds, when the implosion and radial oscillations occur; secondly, during the adiabatic compression and during the crowbarred phase. Diffusion at early times was studied by comparing the density distributions at 2 and 5 μsec with theoretical predictions from the code started at the beginning of the main current pulse, using the measured properties of the preionized gas as the initial conditions. In the second stage the diffusion was measured by comparing the data with computations started at 5 μsec and using as initial conditions the measured temperature and density distributions within the discharge at that time, together with the measured time variation of the external magnetic field. The time variation of the density on the axis is sensitive to the diffusion rate, and a comparison between the observed variation and computations assuming different resistivities, yields an additional value of the diffusion coefficient[29].

5. EXPERIMENTAL RESULTS

Figs.5(a) and (b) show the experimental radial density distributions at 2 and 5 μsec, compared with theoretical curves calculated assuming various resistivities. When including the Bohm term from early times η_B was written as $\eta\left(1+\frac{\omega_{ci}\,\tau_{ei}}{16}\right)$, since as $\omega_{ce}\,\tau_{ei}/16$ approaches zero the resistivity follows the classical value. The theoretical curves in Fig.5(a) were computed using resistivities η, 100η and η_B. In the first two cases there is a relatively sharp density gradient in the outer regions. The distribution with the Bohm term is diffuse and in reasonable agreement with the measurements. Fig.5(b) shows how the distributions have developed at 5 μsec; two theoretical curves are shown with the Bohm term - in one this term is retained for 5 μsec and in the other it is removed at 1·5 μsec. Both are of the observed shape but the latter is in much better agreement with the data. When the Bohm term is retained the theoretical profile shows much greater diffusion than was observed, the reduction in the density on the axis in the theoretical distribution being particularly marked.

Fig.6 shows the density on the axis as a function of time during a crowbarred discharge with a peak temperature of 120 eV, compared with the theoretically predicted time variation for three different resistivities. The experimental points lie closest to theory for classical diffusion. Data at 90 and 160 eV showed similar behaviour. Fig.7 shows the measured density distribution at three different times during the crowbarred phase for the discharge at 120 eV; the theoretical curves were calculated assuming the classical diffusion coefficient and no energy loss, and the computation was started at 5 μsec. The experimental points are in good agreement with the computations at 16 μsec and at 22 μsec except for a small discrepancy near the axis, of the order of the experimental error, estimated to be about ± 10-15% in this region. It is seen from these curves that changes in the distribution are accurately predicted assuming classical diffusion. Similar agreement was found at 90 eV and at 160 eV, the results for which are shown in Fig.8. In this case it is seen that at 18 μsec the experimental points depart from the theoretical distributions in the manner expected for enhanced diffusion. This departure is always found a few microseconds before the onset of the residual instability (section 3), in agreement with earlier work[14].

Fig.9 shows, for the discharge at 120 eV, an experimental distribution at 20 μsec compared with computations assuming classical and Bohm resistivities. It is seen that the experimental points lie on the classical curve and the curve for one tenth of the Bohm resistivity lies outside the experimental errors. In the outer regions where the gradients are small and the diffusion rate is slow the difference between all cases is relatively small.

6. DISCUSSION OF RESULTS

Before discussing the results on the diffusion it is worthwhile commenting on the importance of establishing that the discharge is free of energy losses. An energy or particle loss changes the radial density distribution in the direction opposite to that resulting from diffusion; it is thus possible for diffusion effects to be masked in the presence of an energy loss. Changes in the density distribution due to energy losses are sensitive to the value of β, and become large when β approaches unity. For the present experiment where β on the axis is about 0·7 the presence of trapped flux reduces the effects of energy loss and the cooling time would need to be comparable to the Bohm time (5-10 μsec) to have a significant effect on the density distribution. The experimental evidence for the absence of energy or particle losses was presented in Fig.3, which shows that energy and particles are conserved in the mid-plane for some 25 μsec (at 120 eV) within the experimental error of 10-15%. These measurements are in agreement with the theoretically calculated cooling times for thermal conduction, radiation loss at the measured impurity concentration of about ½% and for particle losses assuming Wesson's[27] theory and the measured plasma properties. Thus in the present experiment the effect of energy loss on the electron density distribution may be neglected, and changes in the distribution can only result from diffusion or the adiabatic variation due to the external magnetic field.

The results presented in Fig.5, demonstrate anomalous diffusion in the early stages. It has been shown elsewhere[14] that the experimental distributions cannot be explained by the effect of impurities or partial ionization or even moderate departures from the initial distributions of temperature and density. The curves in Fig.5 also show that the resistivity is non-classical in character, since the use of the Bohm resistivity gives a profile of the correct shape, while that with a hundred times classical resistivity does not. A comparison between the curve in which the artificial Bohm term was removed at 1·5 μsec and that in which it was retained, indicates that the anomalous diffusion takes place before about 1·5 μsec. An important physical difference between the Bohm and classical resistivities is the temperature dependence; it is the $T_e^{-3/2}$ variation in the Spitzer expression which leads to a sharp current sheath and a square density profile with high beta in the classical computations. Even using 100 times classical leads to a relatively sharp sheath. Anomalous diffusion leading to a diffuse density distribution and a value of β less than unity is now well established in low pressure theta pinch experiments. The present results are important because they demonstrate that this occurs in the early stages of the discharge and cannot be a consequence of end effects.

Three explanations for anomalous diffusion at low starting pressures have been suggested. Morse[30] has shown that if the radial electric field is short-circuited by end effects then the density distribution will be diffuse. However, the short circuit propagates in from the ends with the Alfven velocity, and cannot influence the mid-plane in the early stages of the present experiment. Secondly, anomalous diffusion can arise from hydromagnetic instabilities in the implosion phase, where there are radial accelerations; this mechanism supposes that there are turbulent fluctuations due to the short wavelength hydromagnetic instabilities in the boundary, coupled with classical resistivity at steep gradients set up by these short wavelength flutes. Such a process could lead to a mixing of the plasma and the magnetic field, but approximate calculations could neither account for the observed diffusion rate nor the shape of the density distribution. This mechanism, although not definitely eliminated, is not believed to be likely. The third mechanism involves electron-ion streaming in the sheath and preliminary calculations suggest that this can explain the results. It has the attractive features that it will not occur in discharges at high initial pressures, where the streaming velocity is lower, and sharp sheaths and high beta values have been found experimentally[31]. Furthermore it automatically cuts itself off after one or two microseconds when the current sheath broadens and the density increases, reducing the electron drift velocity. It can be shown that the streaming mechanism leads to a form of the resistivity similar to the Bohm term used here, and this is discussed in a separate publication[32].

During the quasi-steady crowbarred phase of the discharge in time development of the density distribution can be compared with the results of numerical computations based on any type of diffusion process which is theoretically predicted. This has been done rigorously for classical diffusion and the results represented in Figs.6-9 show good agreement. The comparison between the experimental data and computations using the Bohm resistivities (Section 4 and Appendix) in Fig.6 is an attempt to estimate an upper limit of the measured diffusion coefficient compared with that given by Bohm.

The latter was chosen because, firstly, in the form of the "Bohm time"[8] (see below) it appears to be characteristic of many experiments; secondly, diffusion coefficients with the Bohm scaling have been predicted theoretically for various microinstabilities. In Fig.6 the theoretical curve for the time variation of the density on the axis for one tenth of the Bohm resistivity just comes outside the experimental error; the results on the axis are slightly more uncertain than at other radii (Section 5). In Fig.9 the corresponding profile lies well outside the error. It is worth noting that in Fig.6 the curves for classical and Bohm resistivities depart most markedly from one another between 5 and 10 μsec; thereafter they are roughly parallel in both cases. This is because when the diffusion coefficient is large the profile quickly relaxes and the density gradients fall, thus reducing the subsequent diffusion velocity. This also explains why the difference between the two profiles in Fig.9 with the artificial resistivities (η_B and $\eta_B/10$) is less marked than might have been expected.

In experiments where a direct measurement of the diffusion coefficient is not possible the confinement time is often expressed in terms of the empirical "Bohm time" of Hinnov and Bishop for the C-Stellarator given by[8]

$$\tau_B = \pi r^2 (eB/ckT_e)\ F$$

where r is the plasma radius, F is a dimensionless number about unity and the other symbols are as usual. For the value of r chosen and assumed density gradient in the Stellarator this time was stated to correspond to a diffusion rate given by Bohm's coefficient. In general, however, although a comparison with the Bohm diffusion time is a useful way of expressing the confinement time in an experiment, it gives no indication of whether the containment is limited by a diffusion or other process. In the present case the plasma lifetime in the midplane is limited to 2–4 Bohm times by end effects and not diffusion.

The results obtained at three different temperatures corresponding to values of $\omega_{ce}\,\tau_{ei}/16$ from about 20 to 40 on the axis showed the same behaviour. Thus, in all the conditions studied the time variation of the density distribution agrees with classical theory within the experimental error of some 10%, which corresponds to a diffusion coefficient within a factor of about 2 of the classical value. From the comparison between the experimental data and the computations using the Bohm resistivities, and taking into account the uncertainty in the numerical factor (see Appendix) and the experimental error, the measured coefficient is probably less than one tenth of the Bohm value of $1/16\ ckT_e/eB$.

A comparison between the present experiment and those where the observed confinement time was limited to about one Bohm time reveals three main differences; firstly, the plasma in the present case is confined in the simplest possible field configuration - a uniform axial magnetic field - compared with more complicated toroidal fields; secondly, it is collision dominated and the mean free path is comparable to the diameter; thirdly, the plasma beta is much larger. Of these three factors, the most likely one to explain the different diffusion rate is the high beta. It has been shown(33) for collision dominated plasma that a resistive drift instability can lead to diffusion at approximately the Bohm rate, and for the observed plasma parameter such an instability might have been expected to grow in about 1/10th of the Bohm time. The collision-free resonant particle drift instability has been shown(11) to be stabilised when beta exceeds 10%, and it is suggested that in the present experiment the collisional drift instability may also be stabilised by high beta effects.

7. CONCLUSIONS

The perpendicular diffusion coefficient has been measured directly in a theta pinch by comparing the time variation of the density distribution with the computed variation assuming classical and other resistivities. The plasma is collision-dominated with a density on the axis of $3\text{–}4 \times 10^{16}$ electrons/cc and measurements were made at temperatures 90, 120 and 160 eV, with beta on the axis about 0·7. The plasma in the midplane was shown to be free of energy losses and uninfluenced by the ends for 20-25 μsec.

During the first two microseconds anomalous diffusion at approximately the Bohm rate is found, and this is believed to be due to a streaming mechanism. Thereafter, in all conditions studied, the time variation of the density distribution agrees with classical theory for binary collisions, within the experimental error of about 10%; this corresponds to a diffusion coefficient within a factor or two of the classical value. The observed coefficient is probably less than one tenth of the Bohm value given by 1/16 ckT_e/eB.

8. ACKNOWLEDGEMENTS

The authors wish to thank J. McCartan for several helpful suggestions, in particular on diffusion on the early stages, and to acknowledge their colleagues, J.A. Reynolds, G.H. Wolf, G.C.H. Heywood, A.D. Beach, C.A. Bunting, D.J. Dancy, M.R. Kenward, I.K. Pasco, R. Peacock and J.L. Watson for discussions and/or help in carrying out the measurements.

9. REFERENCES

1. L.M. GOLDMAN, H.C. POLLOCK, J.A. REYNOLDS and W.F. WESTENDORP, Phys. Rev. Letters 9, 361 (1962).

2. W.E. QUINN, E.M. LITTLE, F.L. RIBE and G.A. SAWYER, in Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, 1966), vol.1, p.237.

3. H.A.B. BODIN, T.S. GREEN, A.A. NEWTON, G.B.F. NIBLETT and J.A. REYNOLDS, in Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, 1966), vol.1, p.193.

4. C. ANDELFINGER, G. DECKER, E. FUNFER, A. HEISS, M. KEILHACKER, J. SOMMER and M. ULRICH, in Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, 1966), vol.1, p.249.

5. T.S. GREEN, D.L. FISHER, A.H. GABRIEL, F.J. MORGAN and A.A. NEWTON. Phys. Fluids 10, 1663 (1967).

6. C. ANDELFINGER, G. DECKER, E. FUNFER, H. HERMANSDORFER, M. KEILHACKER, E. REMY, M. ULRICH, H. WOBIG and G.H. WOLF. IPP/155, 1966.

7. E. HINTZ and A.C. KOLB, Phys. Fluids 8, 1347 (1965).

8. E. HINNOV and A.S. BISHOP, Phys. Fluids 9, 195 (1966).

9. F. BOESCHOTEN, (J. Nucl. Energy Pt.C) 6, 339 (1964).

10. L. SPITZER, Physics of Fully Ionized Gases (Interscience Publishers, Inc., New York, 1956), Chapter 3.

11. L. MIKHAILOVSKAYA and A. MIKHAILOVSKII, Zh. Eksp. Teor. Fiz. 18, 1077 (1964) [Sov. Phys.]

12. E.A. McLEAN, A.D. ANDERSON and H.R. GRIEM, Los Alamos LA-3770, Paper A5.

13. T.K. ALLEN, H. COXELL, M. HILL and I.J. SPALDING, Los Alamos LA-3770 Paper G4.

14. H.A.B. BODIN and D.J. DANCY, Nucl. Fusion 7, 191 (1967).

15. L.E. GRIBBLE, E.M. LITTLE and W.E. QUINN, Los Alamos LA-3770 Paper A-3.

16. G. HAIN, K. HAIN, K.V. ROBERTS, S.J. ROBERTS and W. KOPPENDORFER, Z. Naturforsch. 15a, 1039 (1960).

17. H.A.B. BODIN and A.A. NEWTON, Los Alamos LA-3770 Paper A2.

18. N.R. McCORMICK, IEE Proc. Culham Report CLM-P 130 (1966).

19. D. BAYES, R.J. HUCKLESBY and B.J. WARD. Frascati Conference, 4th Symposium on Engineering Problems in Thermonuclear Research, (1966).

20. A.A. NEWTON, Culham Report CLM-R 62 (1966).

21. A.D. BEACH, AWRE-Report O-42/67.

22. H.A.B. BODIN et al. to be published.

23. T.S. GREEN, Nuclear Fusion 2, 92 (1962).

24. A.A. NEWTON, Nuclear Fusion 8, 93 (1968).

25. D.J. DANCY and M. KEILHACKER. Culham Laboratory CLM-M 55 (1965).

26. H.A.B. BODIN and B. McNAMARA, Plasma Physics 9, 505 (1967).

27. J.A. WESSON, in Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, 1966), vol.1, p.223.

28. H.A.B. BODIN, A.A. NEWTON, J.A. WESSON and G.H. WOLF. Culham Report CLM-P 184 (1968).

29. H.A.B. BODIN and A.A. NEWTON, Am. Phys. Soc. 13, 318 (1968).

30. R.L. MORSE, Phys. Fluids, 11, 7 (1968), p.1558.

31. E. HINTZ, Nucl. Fusion. Suppl. Pt. 2, 601 (1962).

32. H.A.B. BODIN, J. McCARTAN, A.A. NEWTON and G.H. WOLF, 3rd Conf. Plasma Physics (Novosibirsk August 1968) Paper CN24/K1.

33. M.N. ROSENBLUTH. Invited paper at New York Meeting of American Physics Society (1967).

APPENDIX

COMPARISON WITH THE BOHM DIFFUSION COEFFICIENT

The classical diffusion velocity is given by (ref. 10, eq.(3.16))

$$v_\perp = -\frac{\eta}{B^2}\nabla p \qquad \ldots (A.1)$$

and in order to compute the time variation of the density distribution for diffusion with Bohm's empirical coefficient a Bohm resistivity, η_B, is chosen, such that when it replaces η in eq.(A.1) the Bohm diffusion velocity results, i.e.

$$v_B = -\frac{\eta_B}{B^2}\nabla p$$

v_B can be written (ref.10, eq.(3.19))

$$v_B = -\frac{c}{16\ enB}\nabla p\ . \qquad \ldots (A.2)$$

Thus

$$\eta_B = \frac{cB}{16\ en}$$

which can be expressed

$$\eta_B = \frac{\omega_{ce}\ \tau_{ei}}{16}\ \eta \qquad \ldots (A.3)$$

where the symbols have their usual meanings. This value, derived from Spitzer's equations, is used in the computations in the present paper.

Although the classical expression contains the product of the resistivity (depending on T_e) and the pressure (depending on $T_e + T_i$) the velocity found by Bohm (in a plasma where $T_e \ll T_i$) only contains T_e. Bohm's original coefficient $D_B \sim \frac{1}{16}\ ckT_e/eB$ follows at once from eq.(A.2) if $\nabla p = kT_e\ \nabla n$. Indeed, in most cases it is believed that turbulent diffusion due to micro-instabilities depends on the electron temperature, since this determines the fluctuating electric fields. For example, a diffusion coefficient of the order ckT_e/eB has been derived[33] for the resistive drift instability, although the numerical factor has not yet been calculated. Assuming Bohm's empirical factor of $\frac{1}{16}$ and that is is the electron temperature which enters the expression for the Bohm diffusion velocity, the right hand side of eq.(A.3) should be multiplied by $T_e/(T_e + T_i)$; this is about ½ in the present experiment. Thus the value used could lead to an over-estimate of the Bohm diffusion rate by a factor of 2; uncertainties of this order are certainly possible in the qualitative treatment given here.

TABLE I

PARAMETERS OF EXPERIMENT

BANK

Energy	= 1.1 MJ
Voltage	= 40 kV
Capacity	= 1382 μF
Inductance	= 2.8 nH
Added Inductance	= 0–4.3 nH
Total Inductance (including coil)	= 4.6–8.9 nH

ELECTRICAL CHARACTERISTICS
Ringing

Half period	= 11.0 μsec
Peak current	= 14.7 MA
Peak field	= 24 kG
Initial dB/dt	= 8.0×10^{9} g sec^{-1}

COIL

Length (32 sections)	= 7.71 m
Bore	= 11 cm
Tube	= 8.3 cm

CROWBAR

Time to 1/e	= 160 μsec
Ripple	± 15%

TABLE II

MEASURED PLASMA PROPERTIES AT 20 MTORR

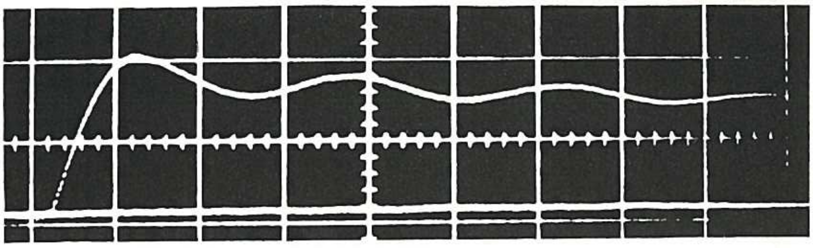
V (kV)	B (kG)	$n_e \times 10^{16} cc^{-1}$ (on axis)	T_e (eV) (on axis)
30	18 ± 1	3 ± 0·5	90 ± 15
34	20 ± 1	3 ± 0·5	120 ± 15
40	24 ± 1	3·5 ± 0·5	160 ± 20

TABLE III

PLASMA PARAMETERS AT 20 MTORR and 34 kV (DEDUCED FROM TABLE II)

(At peak magnetic field, and where quantities vary with radius the values on the axis are given)

Beta	β	= 0·7 ± 0·2
Plasma radius	r_p	= 1-2 cm
Ion Larmor radius	r_{Li}	= 1 mm
Mean free path	λ	= 1 cm
Ion-electron equipartition time	τ_{eq}	= 2 μsec
Cyclotron frequency/collision frequency	$\frac{\omega_{ce}\ \tau_{ei}}{16}$	= 30



5 μsec/cm

Fig. 1 Oscillogram of magnetic field waveform (CLM-P 185)

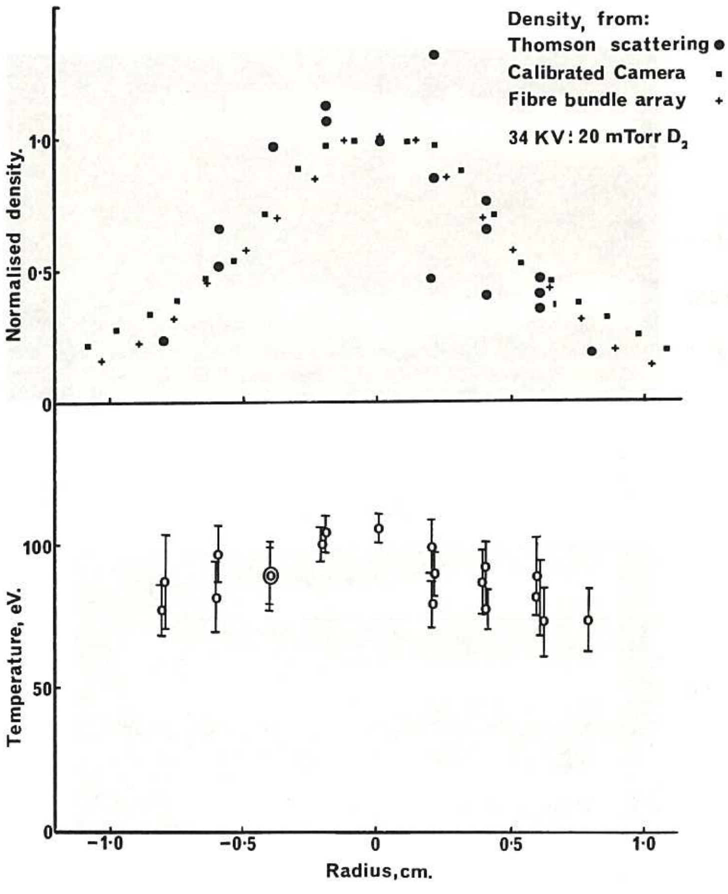


Fig. 2 (CLM-P 185)

Experimental radial density distribution obtained by three different methods. The radial temperature distribution obtained by Thomson scattering is also shown

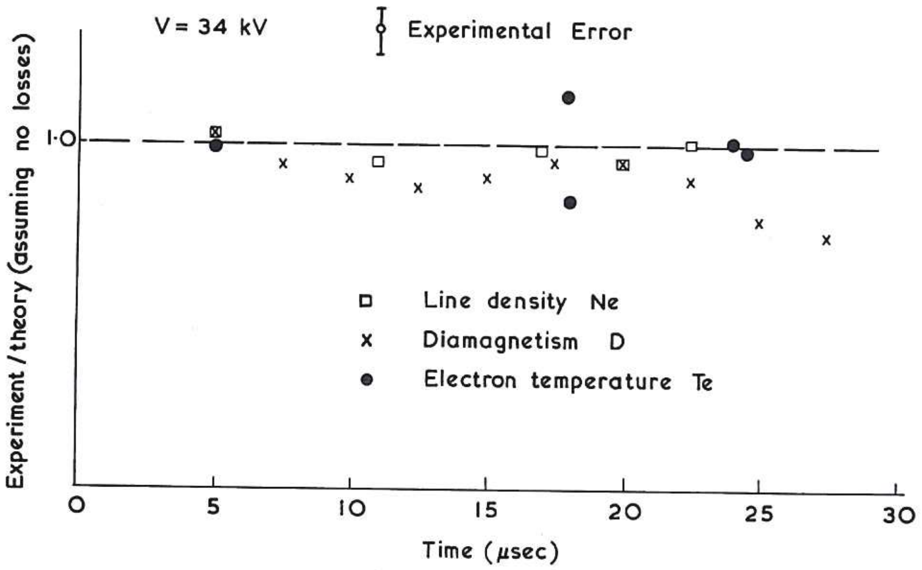


Fig. 3 (CLM-P 185)
Time variation of the diamagnetic signal, the line density, and the electron temperature, expressed as ratios to the theoretical values calculated assuming adiabatic behaviour and no energy or particle losses

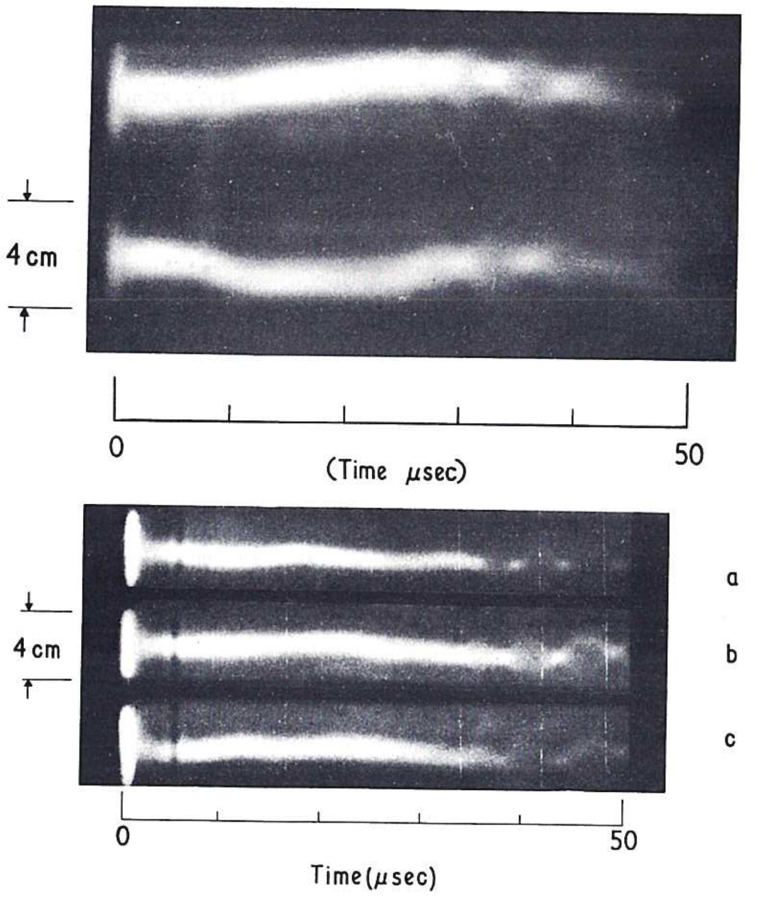


Fig. 4 (CLM-P 185)
Streak photographs in the mid-plane (stereoscopic) and at three other axial positions showing the onset of the residual instability at about 30 μsec

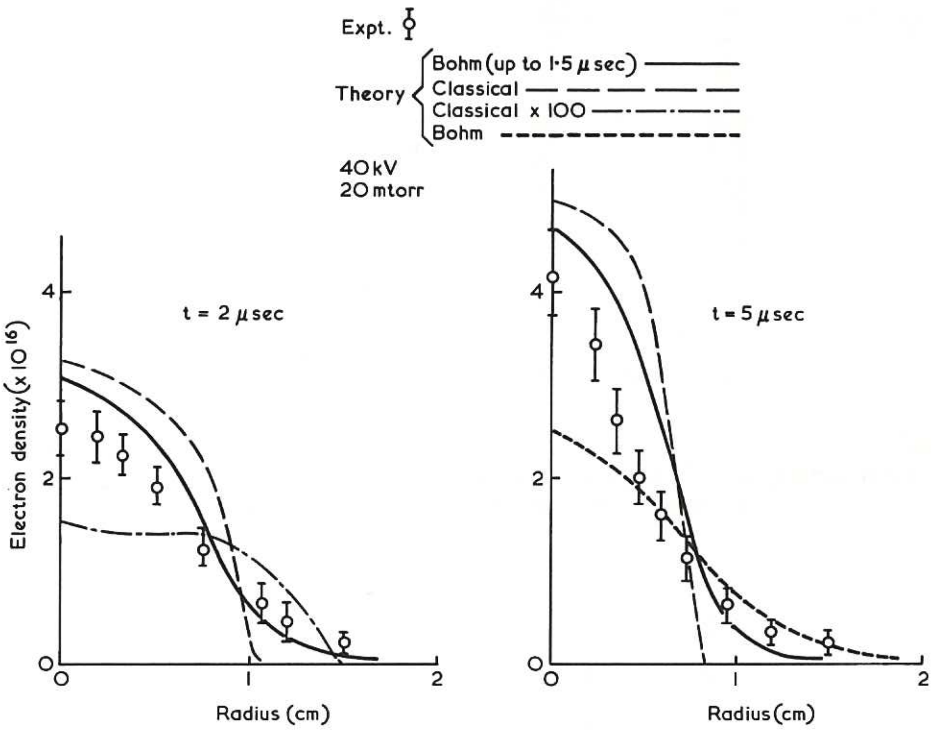


Fig. 5 (CLM-P 185)

Electron density distributions at 2 and 5 μsec; experiment and theory calculated assuming various resistivities

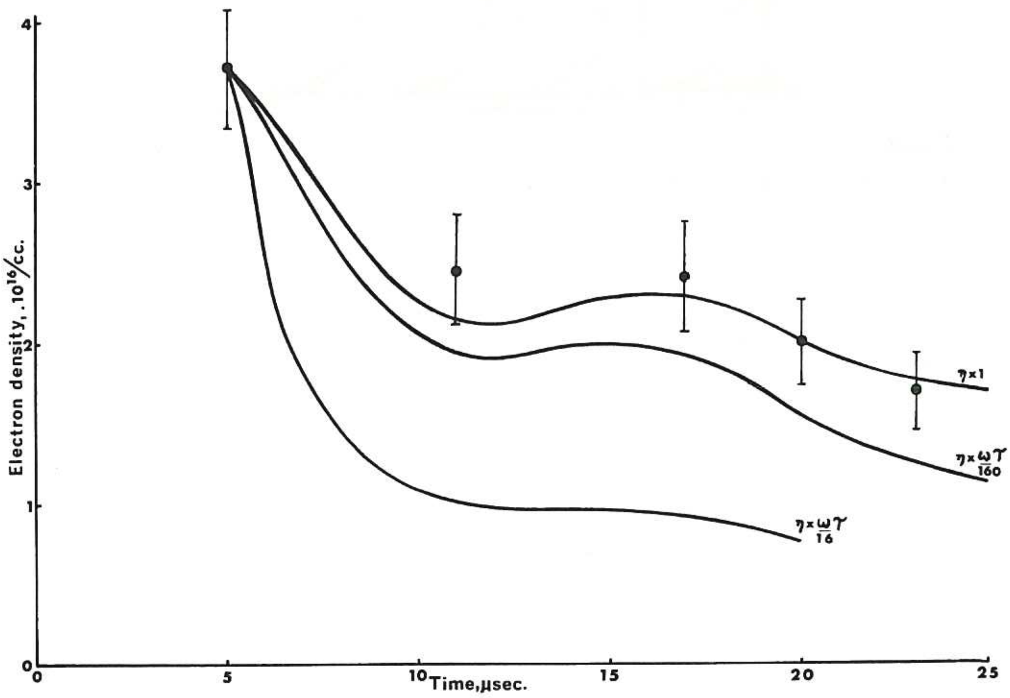


Fig. 6 (CLM-P 185)

The electron density on the axis as a function of time-experiment and theory assuming various resistivities

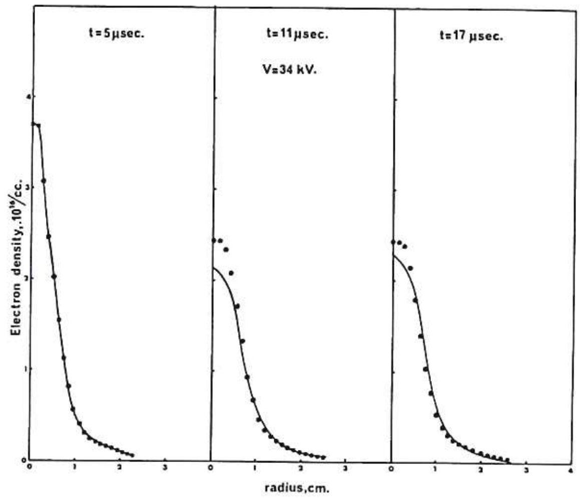


Fig. 7 (CLM-P 185)
Electron density distributions at various times – experiment and theory assuming classical diffusion – for a discharge at 120 eV

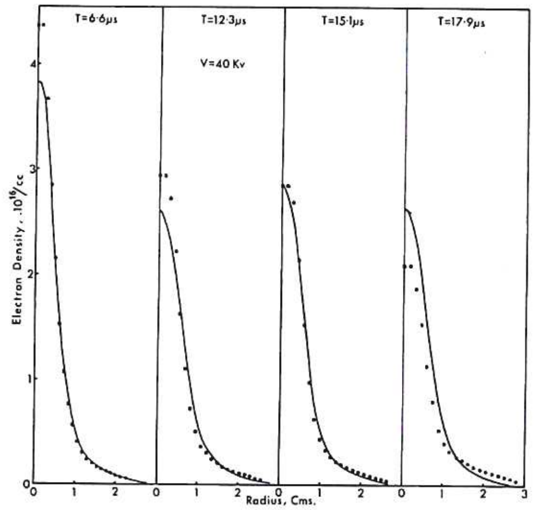


Fig. 8 (CLM-P 185)
Electron density distributions at various times - experiment and theory assuming classical diffusion – for a discharge at 160 eV

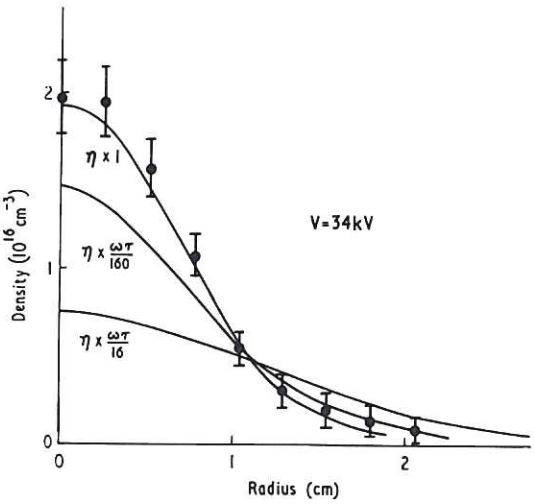


Fig. 9 (CLM-P 185)
Radial electron density distributions at 20 μsec – experiment and theory assuming different resistivities