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RADIAL IMPLOSION OF A PARTIALLY IONIZED PLASMA IN A THETA-PINCH

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ABSTRACT

An investigation has been made of the radial implosion of a deuterium plasma in a theta-pinch under conditions in which the initial level of ionization was controlled. Measurements were made of the diamagnetism of the plasma during the implosion and these have been related to the mass of gas in motion. The latter depends on the interaction between the ions and the neutral atoms. Analysis of the data shows that the effective cross-section for momentum transfer from ions to neutrals is $4 \times 10^{-15} cm^2$. This is close to the charge exchange cross-section for protons and hydrogen atoms.

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CONTENTS

1. INTRODUCTION

The need to define the initial conditions in Theta-pinch experiments has led to the development of methods to ionise the gas prior to the pinch [1 -4]. As a consequence we have studied the influence of the level of ionisation in the gas on the radial implosion as part of the programme of the Megajoula Theta-pinch experiment in the Culham Laboratory [1]. The experimental investigation is supplemented by a numerical computation programme for the partially ionised plasma in a theta pinch devised by Roberts [5].

Experimental and theoretical investigations of this problem have also been reported by Eberhagen and Keilhacker [6] and Ducks [7].

Measurements have been made of the plasma diamagnetism [8], that is of the flux perturbation caused by the plasma, during the radial implosion. The plasma diamagnetic signal, S, rises from zero to a maximum during the pinch, falling to a minimum at the end of the pinch. The value of the signal at the maximum has been found to depend on the initial gas pressure and the electron density in the pre-ionised gas.

To explain this dependence we have developed a theory, presented in this paper, relating to the maximum value of the diamagnetic signal to the mass of plasma set in motion. In a partially ionised plasma this mass depends on the interaction between the ionised particles and the neutrals. From a comparison of the experimental data with this theory we have found that the effective cross-section for momentum transfer between ions and neutrals is equal to 4×10^{-15} cm^2. The data is also compared with the predictions of the numerical computations based on the programme devised by Roberts.

2. PRE-IONISATION OF THE GAS AND PROPERTIES OF THE AFTERGLOW

The gas is pre-ionised using an axial current discharge between electrodes separated by 300 cms. The current pulse is shaped and made almost square, using a transmission line. This line has a capacity of 1.0 μF; when charged to 40 kV it provides a 6 μsec duration pulse of 8 kA.

A small sparking plug is mounted in the cathode to give an initiating pulse: this reduces the breakdown time lag to a fraction of a microsecond at pressures above 10 mTorr. Below 10 mTorr breakdown becomes erratic.

The decay of electron density during the afterglow has been monitored using 2 mm and 8 mm microwave interferometers in which one optical path was a diameter of the discharge tube, and using a He - Ne gas laser interferometer of 3.39 μ wavelength in which the optical path was parallel to the tube axis [9]. Fig. 1a shows the mean electron density as a function of time determined using the microwave interferometers. It should be emphasised that since the electron density decays partly by wall recombination, it is not uniform across a diameter but approaches a Bessel distribution (Fig. 1b). Consequently the values obtained with the microwave interferometers are mean values across the diameter and are higher than the densities close to the wall. It will be seen later that this can influence the interpretation of the data.

3. MEASUREMENT OF PLASMA DIAMAGNETISM

The plasma diamagnetism is determined by comparing a measurement of the total flux of axial magnetic field in the discharge tube with a measurement of the field intensity in the region outside the plasma [8]. Earlier techniques used in reference 8 have been modified; the total flux now being measured with a single turn coil wrapped round the discharge tube. The field intensity is measured with a small loop placed between the discharge coil and the discharge tube.

The difference signal between these two coils is measured and is adjusted to zero with no gas in the tube. With plasma the difference signal is non-zero and is proportional to the plasma diamagnetism S (see reference 8).

i.e. $$S = \int_0^{A_p} (B_V - B_p)\, dA$$

where B_V is the vacuum magnetic field and is assumed uniform in space

B_p is the average magnetic field in the plasma

and A_p is the area of the plasma.

In the present experiments no initial magnetic field is used and hence to a first approximation one can equate B_p to zero, assuming that the plasma is separated from the vacuum field by a thin current layer.

Hence $$S = BA_p \qquad \ldots (1)$$

Fig.2 shows the variation of S with time for a discharge at a pressure of 30 mTorr. S rises from zero at field zero, as the magnetic field rises and reaches a maximum and then starts to decrease during the pinch due to the decrease in A_p. Subsequent oscillations correspond to the radial oscillations of the plasma.

4. EXPERIMENTAL RESULTS

The experimental data obtained are shown in Fig.3, the height of the peak in diamagnetism being plotted against pressure for various initial conditions. Experimental points obtained under normal operating conditions (electron density greater than 30% of atom density) are shown as squares: it can be seen that they lie close to a line $S \propto p^{1/4}$. The other points correspond to starting mean electron densities of 10^{12}/cc, 10^{13}/cc and 10^{14}/cc.

5. DISCUSSION OF EXPERIMENTAL RESULTS

(a) Interpretation of Diamagnetic Signals

The maximum on the diamagnetic signal occurs when the time derivative of S is zero, i.e. when

$$A_p \frac{dB}{dt} = -B \frac{dA_p}{dt}$$

or

$$r_p \frac{dB}{dt} = - 2B \frac{dr_p}{dt} \qquad \ldots \quad (2)$$

where r_p is the plasma radius.

In the approximation we are using, of no trapped field, r_p is the radius of the current layer which is also the piston surface. The velocity $\frac{dr_p}{dt}$, of the piston is also given by the momentum balance equation

$$\frac{d}{dt}\left[M.f. \frac{dr_p}{dt}\right] = \frac{B^2}{8\pi} \cdot 2\pi r_p \qquad \ldots \quad (3)$$

where M is the mass (per unit length) in motion and f is the ratio of the mean velocity of the particles to the velocity of the piston.

For a snowplough model of the pinch in which particles stick to the piston f is unity; for a model in which the piston is perfectly reflecting f is two. It will be seen later that the value of S is not very sensitive to f.

Equation (3) can be integrated since B equals $\dot{B}t$ at early times, provided the small variation in r_p is neglected

$$M f \frac{dr_p}{dt} = \frac{B^3}{12\dot{B}} r_p \qquad \ldots \quad (4)$$

Eliminating $\frac{dr_p}{dt}$ from equations (2) and (4) gives

$$B = [6 M f \dot{B}^2]^{1/4} \qquad \ldots \quad (5)$$

To derive a value for the peak diamagnetism it is necessary to know the plasma area at this time. This is found by integrating equation (4), either analytically in a plane geometry approximation or by numerical methods in cylindrical geometry. The results of integration show that the distance which the piston has moved is one fifth of the tube radius by the time of maximum diamagnetic signal. This distance is not dependent on pressure or level of ionisation provided the distribution of particles, ionised and neutral, is uniform. Therefore

$$S = A_T [f M \dot{B}^2]^{1/4} \qquad \ldots \quad (6)$$

where M is the mass of gas in motion after the plasma has moved one fifth of the tube radius i.e. 0.8 cm.

In a fully ionised gas, therefore, S should vary as the fourth root of the pressure: this prediction is consistent with the data obtained when using high levels of ionisation (Fig.3). The low values of S obtained at low initial electron densities therefore indicate incomplete trapping of the gas in a partially ionised plasma.

(b) Gas Trapping in a Partially-Ionised Plasma

In order to understand the experimental data on incomplete trapping we have developed a model which helps us to derive an analytical expression for the mass of gas trapped. The model is that at a given time the piston is moving a certain number of particles, both ionised and neutral; the number of particles increases with time due to interaction with the particles ahead of the piston. The piston collects all of the ionised particles and a fraction of the neutrals. The efficiency of collection of the neutrals is assumed to be determined by one cross-section which is called the momentum transfer cross-section. It is the cross-section for any neutral ahead of the piston to gain the same velocity as the piston by interaction with any one of the particles in the piston, either charged or neutral. In this way we omit discussion of the complex and competing processes by which the transfer occurs.

Two further assumptions are made; they are that cylindrical convergence effects are small in the outer 0.8 cm of the tube so that we can use the plane geometry approximation, and that the neutral and ion densities are uniform.

An expression for the total mass (per unit length) of the particles in motion after the piston has moved a distance x, is derived in the appendix:
It is

$$M = \frac{m_i}{\sigma_m} \log_e \left[(1 - \alpha) + \alpha e^{n_0 \sigma_m x} \right] . 2\pi r_p \qquad \ldots \quad (7)$$

where σ_m is the momentum transfer cross-section;

α is the fraction of ionisation in the gas ahead of the piston;

n_o is the total particle density ahead of the piston;

x is the distance moved; and

m_i is the ion mass.

If $n_o\sigma_m x$ is large compared with unity, $\alpha e^{n_o\sigma_m x}$ is also large over the range of α values used: then equation (7) has a simple form.

$$M = \frac{m_i}{\sigma_m}\left(\log_e \alpha + \sigma_m n_o x\right) . 2\pi r_p . \qquad \ldots \quad (8)$$

Combining this with equation (6) one finds

$$S^4 = S_o^4\left[1 + \frac{1}{n_o\sigma_m x} \log_e \alpha\right] \qquad \ldots \quad (9)$$

where S_o is the diamagnetic signal one would obtain for a fully ionised gas.

The data obtained at 50 mTorr fit this expression quite well (Fig.4). From the slope and intercept one can derive a value for $n_o\sigma_m x$ and hence for σ_m. The value thus obtained is 4×10^{-15} cm^2.

At other pressures $\alpha e^{n_o\sigma_m x}$ is not sufficiently large to justify the approximation involved in equations (8) and (9). Consequently we have calculated M and hence S using the more general expression in equation (6) with a value of 4×10^{-15} cm^2 for σ_m and normalising to the value of S_o obtained at 50 mTorr. The values derived are compared with the experimental data in Fig.3 (see also Fig.5).

In general the agreement is good. Discrepancies do occur at low starting densities; these can be attributed to non-uniformity of the initial electron density which means that the density in the outer 0.8 cm is lower than the mean density across the diameter (see Fig.1b).

(c) Computation of Diamagnetic Signal

The diamagnetic signal can be computed using the numerical programme developed by Roberts for a partially ionised theta pinch [5]. It shows the same features as the experimental curves, and can be used to derive values of the maximum diamagnetic signal S as a function of pressure and ionisation level. The results are shown in Figs.4 and 5.

The agreement with the experimental data is very good. It is also apparent that the computed values agree closely with the values obtained from the analytical expressions (6) and (7). This can be understood by detailed examination of the computations. If one considers the piston at rest, the neutral particles appear to approach it and try to pass through it. If the particles are atoms, then the most probable interaction with the moving plasma is charge exchange. As a result of charge exchange, the atom becomes charged and interacts with the magnetic piston so coming to rest relative to the piston. The original ion which was involved in the interaction is now an atom. However it is rapidly ionised by the electrons. For example at 10 mTorr, at an initial ionisation of 14%, the electron density in the piston is about 10^{15} /cc and the time taken to ionise an atom is about 20 nanosec; this compares with the time to peak diamagnetic signal of nearly 200 nanosec. In the computation this shows as a neutral shock preceeding the fully ionised plasma.

6. CONCLUSION

The variation of the plasma diamagnetism during the radial implosion has been found to be dependent on the level of ionisation in the gas. We have proposed a simple model to explain this dependence and have derived a value of 4×10^{-15} cm^2 for the effective cross-section for transfer of momentum from the moving ions to the background neutrals. This value is close to the charge exchange cross-section for protons and hydrogen atoms [10] suggesting that the dominant process is charge exchange of the ions with background deuterium atoms, these atoms being present in the afterglow of the discharge.

The experimental data also agrees with computations made with Roberts' theta pinch programme for a partially ionised gas.

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APPENDIX

Trapping of gas particles in the piston

The model which we have chosen to describe the interaction of the piston with the gas is as follows.

At a certain time t, the piston has moved a distance x, and there are in motion a number of particles N per cm^2 of piston area. This number increases by interaction with the background gas, two processes being important. Firstly there is collection of all the ions. If the piston moves δx and α is the ionisation fraction of the particles of density n_o, then the number of ions collected is

$$\delta N_1 = \alpha n_o \, \delta x$$

(using the plane geometry approximation). Secondly there is collection of some of the neutrals. As the piston moves a distance δx so there are $(1 - \alpha)\, n_o \, \delta x$ neutrals which may interact with the piston. The probability of any one interacting with any one of the N particles in the piston is $(1 - e^{-N\sigma_m})$ where σ_m is the momentum transfer cross-section. Hence the number of ions collected is

$$\delta N_2 = n_o \, (1 - \alpha) \, (1 - e^{-N\sigma_m})$$

and so

$$\frac{dN}{dx} = n_o \, \alpha + n_o \, (1 - \alpha)(1 - e^{-N\sigma_m})$$

Solving for N, with N equal to zero at x equal to zero,

$$N = \frac{1}{\sigma_m} \log_e \left[(1 - \alpha) + \alpha e^{n_o \sigma_m x} \right]$$

Consequently the mass per unit length of plasma in motion is given by the equation

$$M = \frac{m_i}{\sigma_m} \log_e \left[(1 - \alpha) + \alpha e^{n_o \sigma_m x} \right] . \, 2\pi r_p$$

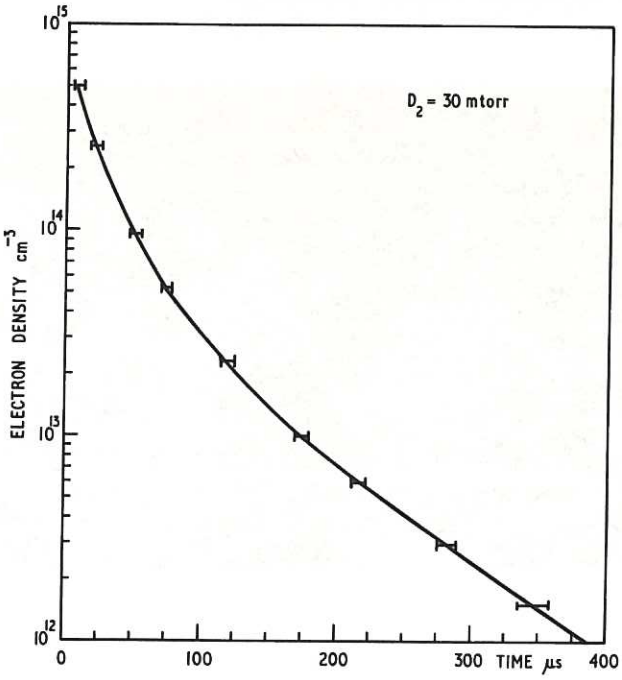


Fig. 1(a) (CLM-P 93)
Decay of electron density in pre-ionization plasma

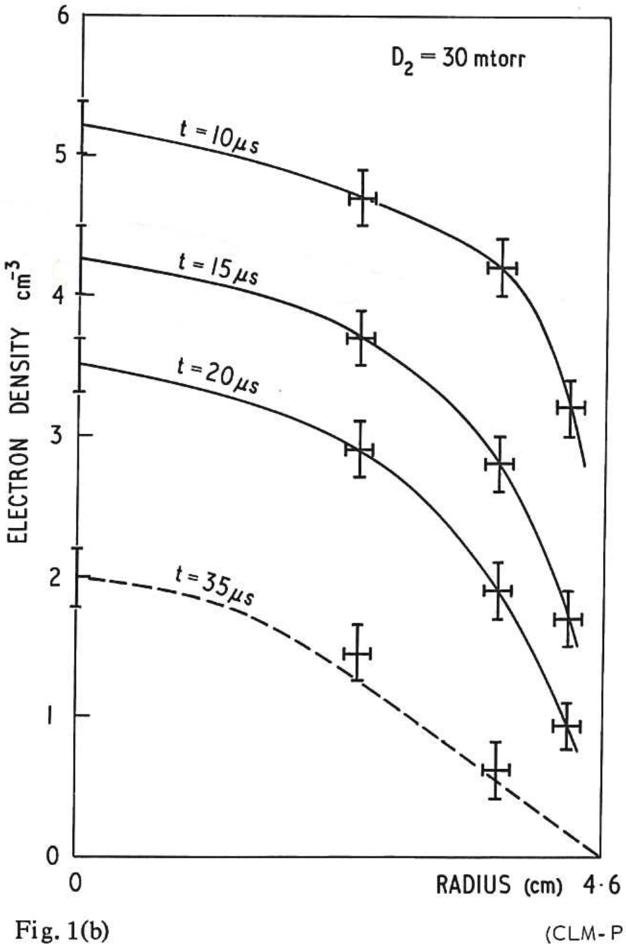


Fig. 1(b) (CLM-P 93)
Radial distribution of electron density in pre-ionization plasma at various times. (The dotted curve is the first order Bessel function J_o (kr) set equal to zero at the tube wall. Tube radius = 4.6 cm

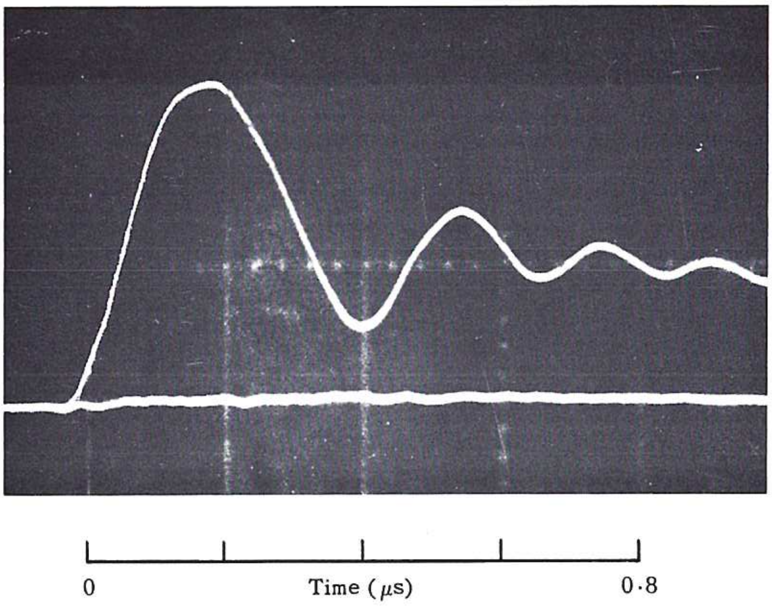
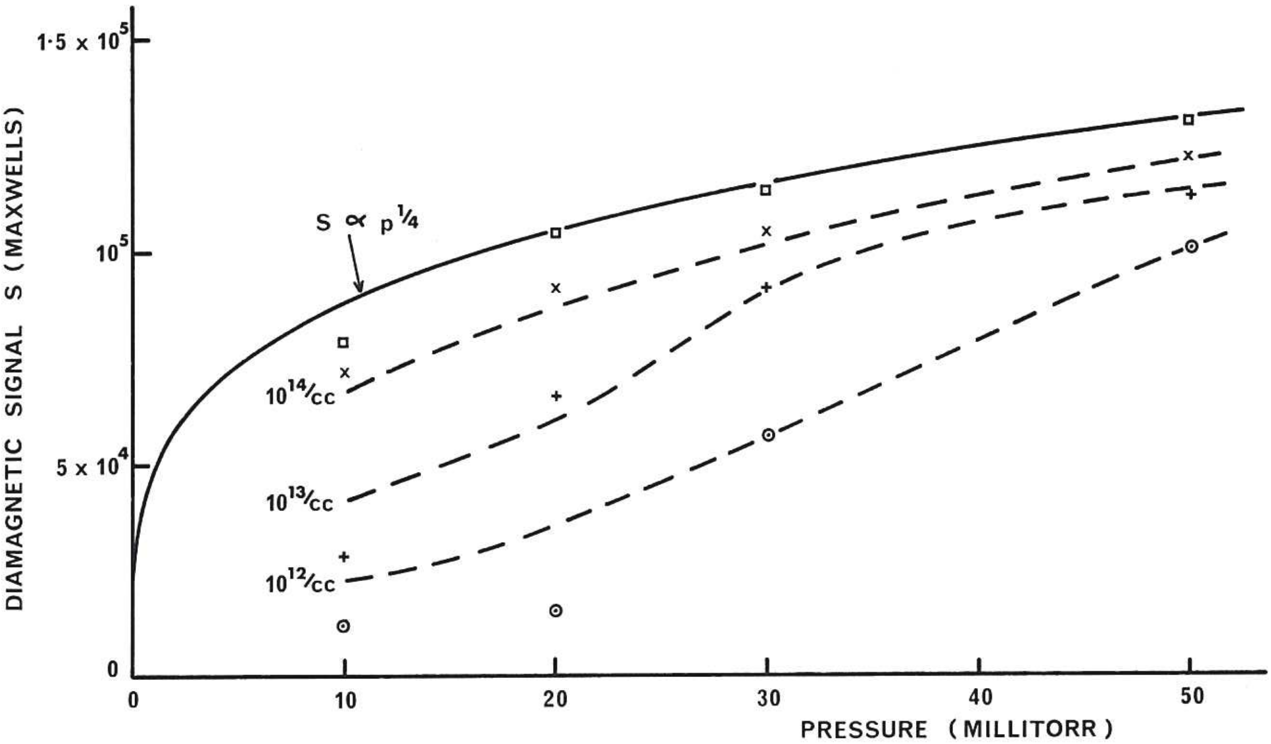


Fig. 2 Oscillogram of diamagnetic signal (CLM-P 93)



DASHED CURVES CALCULATED FROM ANALYSIS WITH $\sigma = 4 \times 10^{-15} cms^2$

□ DATA TAKEN IN NORMAL OPERATING CONDITIONS > 30% IONISATION

x DATA TAKEN AT INITIAL ELECTRON DENSITY OF 10^{14}/cc

+ " " " " " " " 10^{13}/cc

⊙ " " " " " " " 10^{12}/cc

Fig. 3 Peak diamagnetic signal as a function of pressure (CLM-P 93)

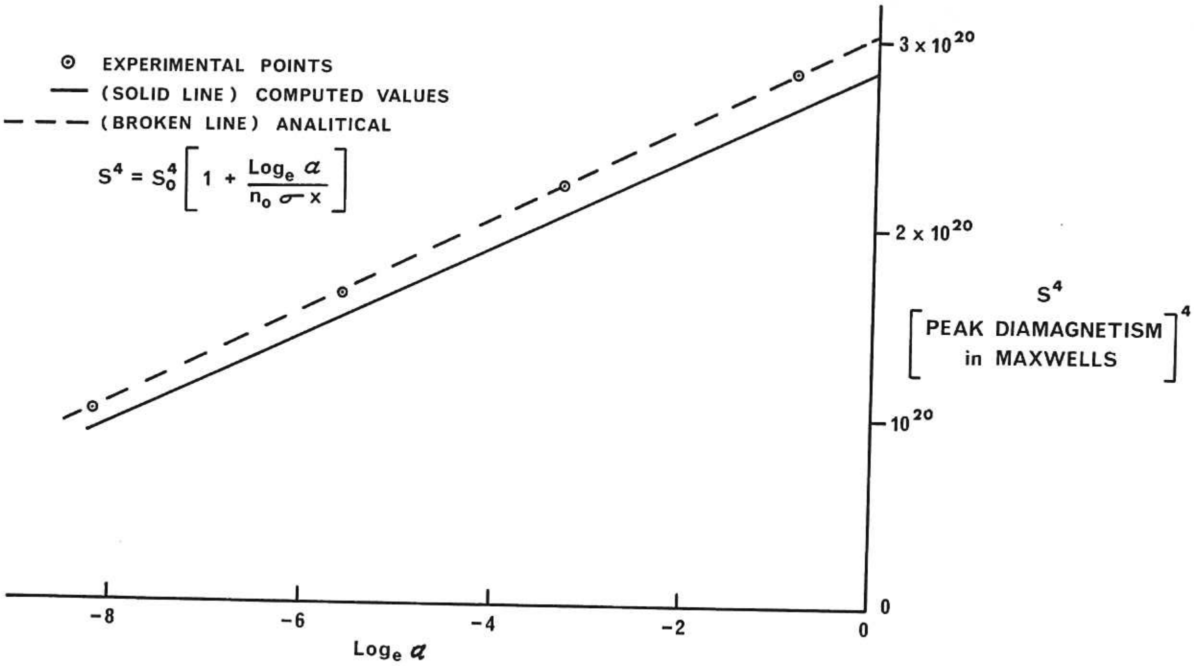


Fig. 4 (CLM-P 93)
Peak diamagnetism versus fraction of ionization (α) at 50 mTorr

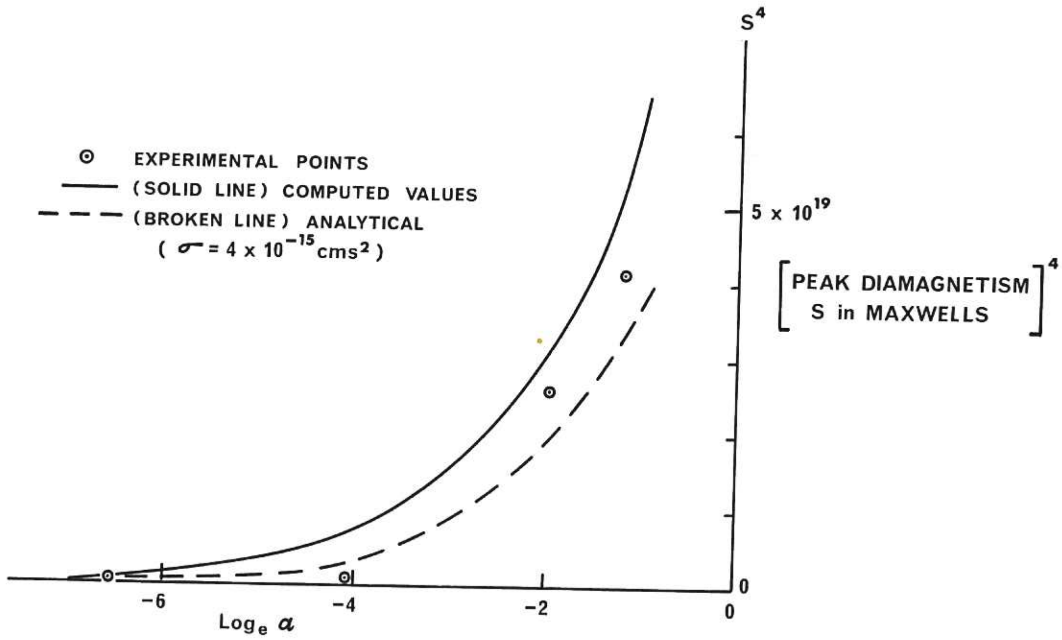


Fig. 5 (CLM-P 93)
Peak diamagnetism versus fraction of ionization (α) at 10 mTorr