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Report

A POTASSIUM BEAM PROBE FOR THE MEASUREMENT OF ELECTRON DENSITY

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ABSTRACT

An apparatus for the production and detection of a beam of mono-energetic potassium atoms is described. By measuring the attenuation of this beam on its passage through a plasma, electron densities may be evaluated. Since the beam velocity exceeds 10^7 cm sec^{-1} rapid changes in density may be observed. This technique has been applied to the plasma produced by a plasma gun, and compared with simultaneous microwave interferometer measurements.

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INTRODUCTION

There are relatively few techniques for the direct measurement of electron density in plasmas of moderate density ($n_e \lesssim 10^{13}$ cm^{-3}). At such densities laser scattering measurements are extremely difficult and absolute intensity measurement of spectral line radiation presupposes a knowledge of the composition of the plasma. Although Langmuir probes and microwave interferometer methods are commonly used their application is not always suitable. Thus Langmuir probes suffer intense plasma bombardment*, and interferometer measurements are difficult to interpret when the plasma exists in a sheared magnetic field (the plasma refractive index then becomes dependent on the magnetic field configuration as well as on the electron density).

In the technique to be described electron density in a plasma is measured by observing the attenuation of a beam of potassium atoms passed through it. For electron temperatures in excess of a few electron volts, ionization by electron impact is the dominant process leading to attenuation so that the degree of attenuation is directly related to the electron density. The potassium beam is unaffected by magnetic fields and since it is relatively tenuous (the potassium atom density in the device to be described was less than 10^5atoms cm^{-3}) it has a negligible effect on the plasma.

Thermal potassium beams have already been used to evaluate electron density(1). Such methods, in which the potassium atoms are produced by the evaporation of potassium in an oven have a limited time response, typically 1 msec, due to the relatively low velocities of the atoms. This defect may be overcome by the use of much faster atomic beams. In our technique a potassium ion beam is accelerated by several kilo electron volts, neutralised by charge exchange and the resultant fast neutral beam used as a probe.

PRINCIPLE

In passing through a plasma of electron density n_e cm^{-3} a beam of potassium atoms, density n_k cm^{-3}, is attenuated by ionization. Thus the beam density $n_k(x)$ at a point x in the plasma is related to its initial density $n_k(o)$ by the usual formula

$$n_k(x) = n_k(o)\, e^{-\int n_e F(\sigma_i v_e v_k)\, dx} \qquad \ldots (1)$$

where σ_i is the cross section for ionization of neutral potassium by electron impact and $F(\sigma_i v_e v_k)$, is in general a complicated function of the electron thermal speed v_e and the potassium atom speed v_k. For $v_e \gg v_k$ however $F(\sigma_i v_e v_k)$ reduces to the simple ratio $\frac{\langle \sigma_i v_e \rangle}{v_k}$. Since in all cases of practical interest this inequality holds, equation (1) gives, after integration

$$\int n_e\, dx = \frac{v_k}{\langle \sigma_i v_e \rangle} \ln \frac{n_k(o)}{n_k(x)} \qquad \ldots (2)$$

Thus a measurement of the beam attenuation ratio $\frac{n_k(o)}{n_k(x)}$ may be used to evaluate the integral $\int n_e\, dx$ in the line of sight of the beam provided $\langle \sigma_i v_e \rangle$ is known. Tabulated below are the values of σ_i and $\sigma_i v_e$ for various electron energies(2,3).

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* For example a Langmuir probe of length 10 cm , diameter 0.5 cm immersed in a 50 eV hydrogen plasma of density 10^{13} cm^{-3} would, as a consequence of the thermal motion of the plasma, result in plasma being lost at the rate of $\approx 4 \times 10^7$cm^3 sec^{-1} with a corresponding energy loss rate of $\approx$ 3 kW.

Electron energy (eV)	11	20	34	50	100	150	200	300	500	
Ionization cross section σ_i (units 10^{-16} cm^2)	9.9	8.0	8.7	8.0	5.6	4.7	4.0	3.3	2.4	
σ_i v_e cm^3 sec^{-1} (units 10^{-7})	1.9	2.1	3.0	3.3	3.3	3.4	3.3	3.3	3.2	

It will be noted that the product σ v_e is relatively insensitive to electron energy in the range 11 eV to 500 eV. Thus, in general it is not necessary to evaluate the mean value of the product σ v_e over the electron velocity distribution. Below about 11 eV however σ_i is a sensitive function of electron energy, falling to zero at the ionization potential 4.3 eV. This dependence of σ_i on electron energy has been used(4) to estimate variations in electron temperature of a relatively cold plasma.

APPARATUS

The potassium beam source

The apparatus used to produce the potassium beam is shown in Fig.1. Potassium vapour emitted by the cylindrical oven is ionized by surface ionization on the hot tungsten ribbon filament(5). This filament, which has an effective area of 1 cm^2 is maintained at 4 kV positive with respect to an extraction electrode. This electrode, together with the aperture of the oven and an intermediate cylindrical electrode form the three elements of an einzel lens which serves to focus the potassium ion beam emitted by the filament. The filament emission current (typically 500 µA) is controlled by varying the oven temperature (about 250°C). After acceleration and focussing, the potassium ions re-enter the oven where they are neutralised by resonance charge exchange on the potassium vapour. The resultant beam emerging from the oven consists almost entirely of atomic potassium.

Detection of the beam

After passing through the plasma the attenuated neutral beam is re-ionized in a gas cell containing about 80 mtorr cms of air. The potassium ions thus formed are separated from the background of particles and ultra-violet radiation emitted from the plasma by means of electrostatic energy analysis(6). The gas cell and detector are identical with the smaller of the two devices described in the above reference except that air, rather than water vapour, is used in the gas cell. A permanent magnet is placed at the entrance to the gas cell to remove any potassium ions produced by ionization of the beam en route from the source*. Fig.2 shows the general arrangement of the source and detector.

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* Apart from ionization by plasma electrons, potassium atoms at the edge of the beam are ionized by grazing incidence collisions with various apertures between the source and the detector. By means of the permanent magnet these ions are removed from the beam so that any further attenuation is due solely to ionization produced by the plasma.

TIME RESOLUTION

The time resolution t_r of the device is determined by the transit time of the potassium atoms through the plasma. Hence if the plasma thickness is d cms in the line of sight of the beam

$$t_r = \frac{d}{v_k} \qquad \dots (3)$$

For a 4 keV beam v_k is 1.4×10^7 cms sec^{-1} so for typical laboratory plasmas t_r is a few μsec.

DENSITY RANGE

The range of electron density, over which the device may be used, is determined by the amplitude of the random fluctuations of the source output current and statistical fluctuations in the detected signal level. Of these two effects the second is most important - the source output current was in fact observed to be very free of random variations. In this case, it may readily be shown that the possible error $\Delta\alpha$ in the measurements of the beam attenuation ratio is given by

$$\frac{\Delta\alpha}{\alpha} \approx \pm \frac{\alpha^{\frac{1}{2}}}{(N_o \cdot t_c)^{\frac{1}{2}}} \qquad \dots (4)$$

where N_o is the number of potassium atoms detected per second and t_c is the response time of the detector circuit. The corresponding error $\Delta \int n_e\,dx$ is, from equations (2) and (4)

$$\frac{\Delta \int n_e dx}{\int n_e dx} = \pm \frac{\alpha^{\frac{1}{2}}}{(N_o \cdot t_c)^{\frac{1}{2}}\ \ell n\alpha} \qquad \dots (5)$$

Taking a typical value of N_o obtained experimentally of $\sim 6 \times 10^8$ atoms sec^{-1} and using a value of $\sigma_i v_e$ equal to 3.3×10^{-7} $\text{cm}^3\ \text{sec}^{-1}$ the following results are obtained from equations (2) and (5)

$\int n_e \cdot dx$ electrons cm^{-2}	α	t_c μsec	$\Delta\int n_e.dx/\int n_e.dx$
4×10^{12}	1.1	1	0.45
		10	0.14
3×10^{13}	2	1	0.084
		10	0.027
1×10^{14}	10	1	0.056
		10	0.018

From the above table it is apparent that in order to measure values of $\int n_e\,dx$ less than about 4×10^{12} electrons cm^{-2} it is necessary to increase the response time t_c.

COMPARISON WITH MICROWAVE MEASUREMENTS

Measurements with this potassium beam technique were compared with measurements made with a microwave interferometer fitted to the M.T.S.E. apparatus(7) in which plasma produced by a coaxial gun is guided into a central magnetic trap where these measurements were made. Fig.3 shows the results of simultaneous measurements by these two methods. The delay of about 20 μsec in the potassium beam signals is due to the distance from the plasma to the detector. It will be noted that the potassium beam probe is better suited to following rapid changes in electron density and the oscilloscope display is more readily interpreted. A quantitative comparison of the two results is complicated by the fact that, since the plasma refractive index does not depend linearly on electron density the value of $\int n_e \, dx$ deduced from the microwave measurements depends on the assumed distribution of electron density in the plasma column. However, the two methods gave results that agreed to within a factor of two.

ACKNOWLEDGEMENTS

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REFERENCES

1. GOTT, Yu.V., IOFFE, M.S., and YUSHMANOV, E.E. Experiments on the accumulation of a hot ion plasma in PR-5. I.A.E.A. Conference on Plasma Physics and Controlled Nuclear Fusion Research, Culham, September, 1965. Proceedings, vol.1, 1966. pp.35-51. (Paper CN-21/143)

2. BRINK, G.O. Absolute ionization cross sections of the alkali metals. Phys. Rev., vol.134, no.2A, 20 April, 1964. pp.345-346.

3. BRINK, G.O. Ionization of alkali atoms by electron bombardment. Phys. Rev., vol.127, no.4, 15 August 1962. pp.1204-1206.

4. EUBANK, H.P. Instrumentation for plasma diagnostics. Phys. Today, vol.19, no.7, July 1966. pp.91-105.

5. DATZ, S. and TAYLOR, E.H. Ionization on platinum and tungsten surfaces. I. The alkali metals. J. Chem. Phys., vol.25, no.3, September 1956. pp.389-394.

6. MASON, D.W. and SCHOFIELD, J.M.S. An apparatus for the detection and energy analysis of fast neutral atoms. London, H.M.S.O., 1966. CLM -R 49.

7. FRANCIS, G., MASON, D.W. and HILL, J.W. Containment of plasma in a magnetic mirror with hexapole stabilizing fields. Nature, vol.203, no.4945, 8 August 1964. pp.623-624.

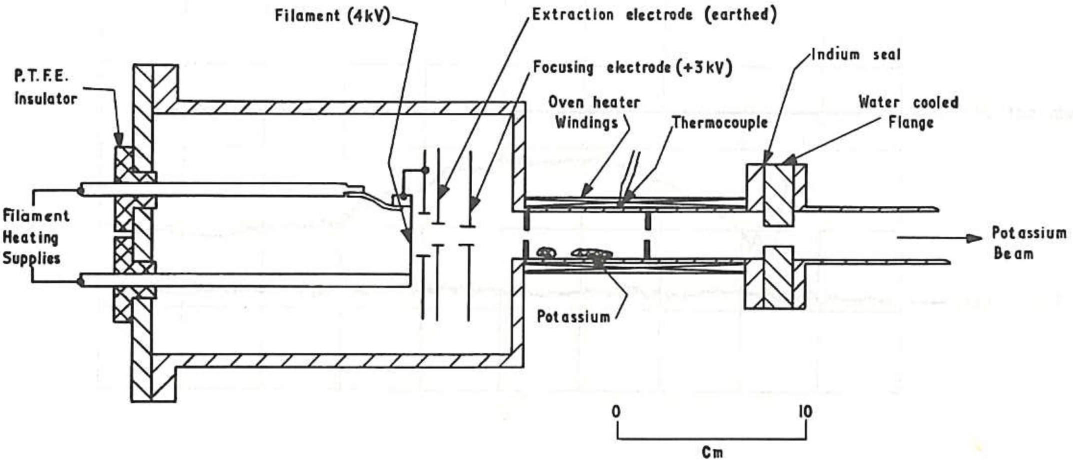

Fig. 1 Source (section) (CLM-R68)

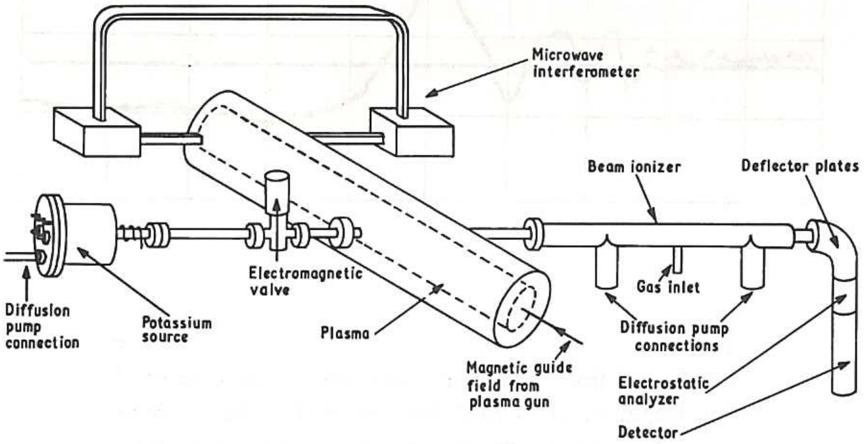

Fig. 2 General arrangement of apparatus (CLM-R68)

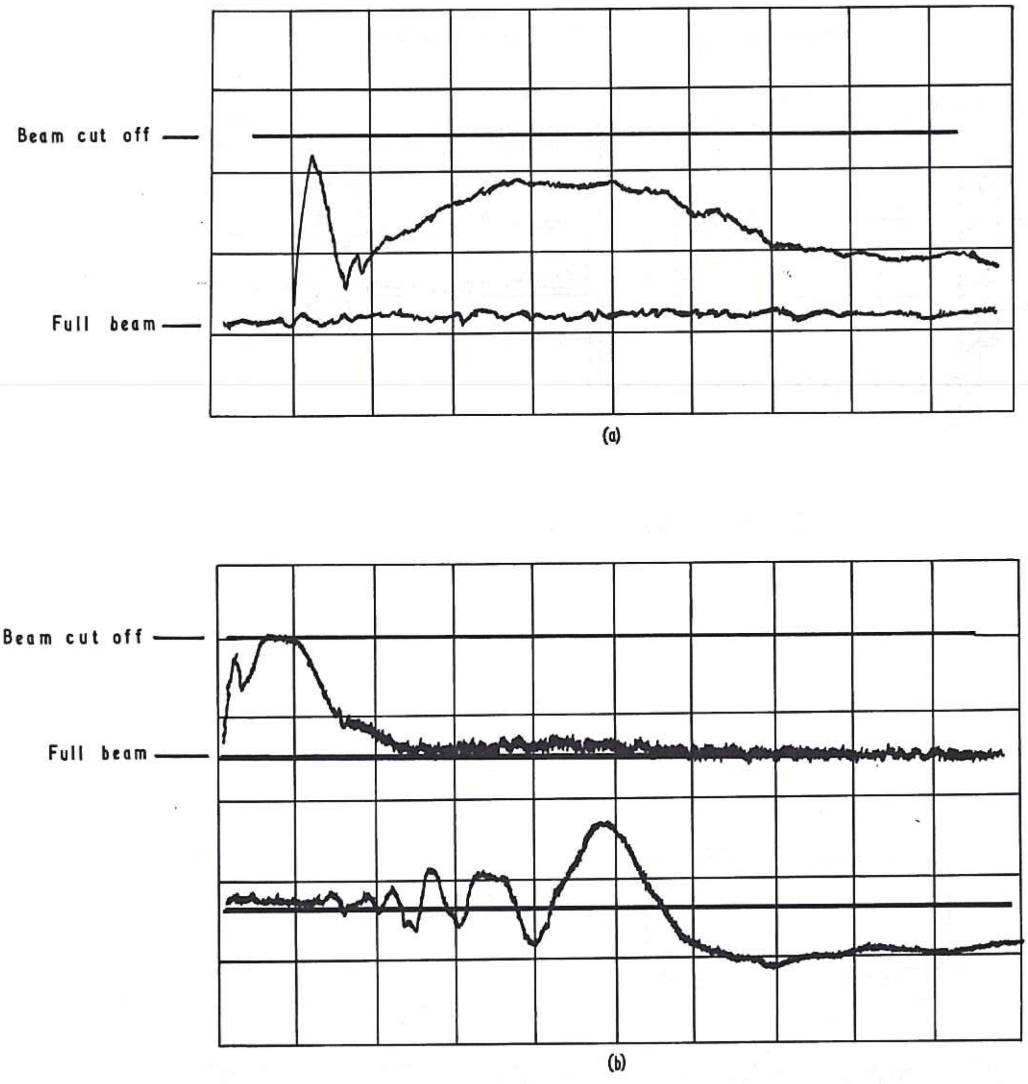

Fig. 3 (CLM-R68)

(a) Signal from potassium beam probe - 20 μsec cm^{-1}

(b) Upper trace: signal from potassium beam probe
Lower trace: microwave interferometer signal - 100 μsec cm^{-1}

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