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FOUR METHODS OF MEASURING THE PLASMA ION ENERGY TRANSVERSE TO A MAGNETIC FIELD

by

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ABSTRACT

Four methods of measuring the thermal energy of the ions of a plasma, transverse to a magnetic field (~ 0.4 Tesla) are compared. The properties of the plasma studied were: duration $800\mu s$, $n_e \sim 2 \times 10^{11}$ cm^{-3}, $T_e \sim 20eV$, $T_i \sim 50eV$ parallel to and ~ 200eV perpendicular to the magnetic field. The magnetic field had a duration ~ 10ms, which allowed penetration into the stainless steel instruments described. The methods of measurement considered, which are applicable only in linear magnetic field systems, were

(i) A method using a conventional gridded energy analyser, exploiting a region of diverging magnetic field to convert the transverse ion energy into longitudinal energy by the principle of adiabatic invariance of magnetic moment.

(ii) A calorimetric method.

(iii) A method described by a previous author(1), which directly measures the Larmor radius of the ions, from which the ion perpendicular energy may be inferred.

(iv) An adaptation of (iii), which is experimentally simpler but justified only when $W_{i\perp}$ is greater than $W_{i\parallel}$.

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1. INTRODUCTION

The measurement of plasma ion energies is of considerable interest in Plasma Physics and Controlled Nuclear Fusion research, yet relatively few methods have been described for the measurement of ion energies $W_{i_\perp}$ transverse to a magnetic field. The measurement of the plasma diamagnetism and number density$^{(2)}$ may be used to infer $W_{i_\perp}$. This measurement usually requires elaborate procedures for balancing out the large signals induced in the measuring coil by any variation of the current in the main magnetic field coils. At ion energies greater than about 1KV, the transverse ion energy of the plasma may also sometimes be measured by observing the energy of neutralised atoms leaving the plasma$^{(2)}$.

In the present paper, four extremely simple methods of measuring plasma transverse ion energy are compared. The hydrogen plasma was produced by a gas-fed transverse injector gun$^{(3,1)}$. The experiments were performed in a linear $\ell=3$ stellarator (Figure (1)). In most of the experiments no helical-winding current was used, so that the magnetic field was set up by the B_z coils alone, with the value of B_z remaining constant up to a few centimetres from the end of the magnetic field coil system. Thereafter, the value of B_z drops (Figure (2)).

2. THE MEASUREMENT OF THE TRANSVERSE COMPONENT OF ION ENERGY.

2.1. Measurement by exploitation of the adiabatic invariance of magnetic moment.

Consider an ion in a region of diverging magnetic field. Using the adiabatic invariance of magnetic moment and the conservation of energy, one obtains

$$W_{i_\parallel}(z) = W_{i_\perp}(o) \cdot \left[1 - \frac{B(z)}{B(o)}\right] + W_{i_\parallel}(o),$$

where $W_{i_\parallel}(z)$ and $W_{i_\perp}(z)$ are the kinetic energies of ion motion parallel and perpendicular to the magnetic field $B(z)$ at position z. A gridded energy analyser$^{(3)}$ was used to measure the kinetic energy $W_{i_\parallel}(z)$ of the ion motion parallel to the divergent magnetic field at various position z in the region at the end of the magnetic field coil system. The energy $W_{i_\parallel}(z)$ is plotted against $\left(B(z)/B(o)\right)$. The intercept on the vertical axis gives $\left(W_{i_\perp}(o) + W_{i_\parallel}(o)\right)$, while the abscissa when $\left(B(z)/B(o)\right) = 1$ is $W_{i_\parallel}(o)$. Hence the perpendicular energy, $W_{i_\perp}(o)$, of the ions in the main magnetic field region, may be obtained. The method of obtaining transverse ion energies by exploitation of the adiabatic invariance of magnetic moment bears some resemblance to a magnetic mirror electric probe method for determining anisotropy of electron temperature in a magnetised plasma(4).

Figure (3) shows a typical energy analyser plot. The average energy of the ions was calculated (a) for a smooth curve drawn through the measured points (E_A) (b) for a curve drawn through the measured points so as to give a maximum conceivable energy E_B, and (c) for a curve giving minimum conceivable energy E_C. The energy recorded by the energy analyser was then taken as E_A, with a positive error bar of $\frac{1}{2}(E_B-E_A)$ and a negative error bar of $\frac{1}{2}(E_A-E_C)$.

The results thus obtained for different values of B(z)/B(o) are plotted in Figure (4). This graph indicates a transverse ion energy of 320eV (± 25%) in the magnetic field. In this experiment, the magnetic field was 0.36 Tesla.

2.2. Calorimetric Measurement of the transverse ion energy.

If a total of N ion-electron pairs hit a calorimeter, and all of the plasma energy is absorbed by the calorimeter, the heat dumped into calorimeter will be

$$eN[W_{i_\perp} + W_{i_\parallel} + W_e] ,$$

where W_e(eV) is the everage energy (total) per electron.

The present experiment was performed with B_z = 0.36 Tesla, I_ℓ = 160 kA. The helical-winding current was necessary in order to make the number N of ion-electron pairs reaching the calorimeter per shot be reasonably reproducible. The number N was measured with a large ion probe(3,1) and was found to be 6×10^{16} (± 25%). The ion energy $W_{i_\parallel}$ was measured with a gridded energy analyser(3,1) and found to be 70eV(± 25%). The electron temperature was measured with a double Langmuir probe (of equal electrode areas) and found to have an upper limit of 25eV. The total energy of the plasma as measured by the calorimeter was 3.64 Joules.

The final result for the ion transverse temperature is

$$W_{i_\perp} = (300 \pm 120)\ \text{eV}$$

2.3. Measurement by means of a Larmor Radius analyser.

Ashby(1) has described an instrument capable of measuring the distribution of ion Larmor radii of a plasma. If the ion species in the plasma is known, the transverse ion energy may be calculated from the formula

$$W_{i_\perp} = \frac{Z^2 e r_L^2 B^2}{2m_i} \quad \text{electron volts,}$$

where r_L metres is the Larmor radius of the ion, B Tesla is the magnetic field, and Ze is the charge on an ion, which has mass m_i kg.

The instrument which is shown in Figure (5) is aligned parallel to the uniform magnetic field. The pinhole diameter is comparable with the Debye length of the plasma, which should prevent any electrons from entering the instrument. In addition, both the cylinder and the plate are biased to -70 volts, which repels any entering electron back to the instrument outer casing. Ions enter the pinhole, gyrating with Larmor radius r_L. An ion is collected by the cylinder if the cylinder radius is less than $2r_L$. Otherwise, the ion is collected by the plate. The currents to the cylinder and plate are recorded by means of the voltage developed across resistors.

Figure (5) shows the fraction of ion current collected by the cylinder, as a function of the cylinder radius. According to the results, ~ 15% of the ions have a Larmor radius greater than 15mm. If all of the ions were H^+, such Larmor radii would correspond to transverse ion energies in excess of 1400 eV. Since such large ion energies have not been detected by any other method, it must be assumed that the plasma has a 15% impurity, of high atomic mass.

Suppose f(r) is the fraction of the ion current detected by the cylinder of radius r and that $f(r) \rightarrow A$ when r is large. To obtain the energy of the H^+ ions, it is necessary to replot the experimental results. Figure (5) also plots $\left(\frac{f(r) - A}{1.0 - A}\right)$ against r, on the assumption that $A = 0.15$. The mean energy of this curve is 160 eV.

2.4. Measurement by means of a modified Larmor Radius Analyser.

The instrument described in the previous section suffers from the disadvantage that the vacuum system must be opened in order to change the cylinders, which makes the measurement time-consuming. The present section describes a modification of the Larmor Radius analyser which may be used if the transverse energy of the plasma ions is greater than the longitudinal energy.

Figure (6) shows the modified instrument. It consists of an outer case with a pinhole, a grid of 99% transparency biased to -70 volts, a hollow cone biased to -70 volts, and a rod biased to -70 volts. The rod can be moved backwards and forwards, through a sliding vacuum seal. If the rod is too far back, $2r_L$ will be greater than the internal radius of the cone at the tip of the rod, and the ion will be collected by the cone. Otherwise the rod collects the ion on one of its returns to the instrument axis.

The instrument gives spurious results if the grid is absent. Without the grid, the ion goes through a radial component of electric field in its journey between the pinhole and the front of the cone. It is believed that the radial component of electric field deflects (by $\underline{E} \times \underline{B}$ drift) the position of the guiding centre of the ion, so that the ion cannot hit the rod. With the grid stationed between the pinhole and the cone, there is no radial electric field, the effect cannot occur, and the results lose their spurious nature.

An optimum half-angle α of the cone exists. Suppose that the front of the cone is of radius R_1, and that the distance between the front of the cone and the pinhole is small compared with the length of the cone. Suppose, also, that the instrument cannot be aligned with the magnetic field more accurately than $\pm\beta$ radians. The error in measuring r_L due to misalignment is

$$(\Delta r_L)_1 = \pm \frac{(R_1 - 2r_L)\beta}{2\alpha}$$

There is a second error in the measurement, because both the rod and the cone can only sample an ion at time intervals of $2\pi/\omega_{ci}$. The error in the measurement of r_L due to this effect is

$$(\Delta r_L)_2 = \pm V_{\parallel} \alpha\pi/2\omega_{ci}$$

where $V_{\parallel}$ is the ion velocity parallel to the magnetic field. The optimum half-angle of the cone is then

$$\alpha = \left[\frac{(R_1 - 2r_L)\beta\omega_{ci}}{V_{\parallel}\pi}\right]^{\frac{1}{2}}, \qquad \ldots(1)$$

and the total fractional error in the measurement is

$$\frac{\Delta r_L}{r_L} = \left[\frac{V_{\parallel}\pi\beta(R_1 - 2r_L)}{\omega_{ci}\, r_L^2}\right]^{\frac{1}{2}}$$

In the present series of experiments, the half-angle α of the cone was made to comply with equation (1). Figure (6) shows the fraction of the total ion current drawn by the cone, plotted against the internal radius of the cone at the position of the tip of the retractable rod. The plot shows the same features as obtained by the Larmor radius analyser of Figure (5). The results were analysed in the same manner as before, with the result that

$$W_{i_\perp} = 160 \text{ eV}$$

3. DISCUSSION AND CONCLUSION

All four methods of measuring the transverse ion energy are extremely simple to use, require only a small amount of experimental time, and are justified when results accurate to within a factor of two are required.

Method (1) depends upon the experimental assembly having a convenient region of diverging magnetic field. Also, this method may be used only if the approximations involved$^{(5)}$ in the proof of the adiabatic invariance of magnetic moment are justified in the particular plasma and magnetic field configuration proposed.

The calorimetric method (method (2)) depends, in part, upon an accurate method of measuring N, the total number of ions falling upon the calorimeter. The method of using a Large ion probe is relatively untested and exposes the measurement to some criticism. However, the results obtained by this method agree with the results obtained by the other methods.

The two Larmor radius analysers gave virtually identical results. In order to obtain the transverse ion energy from these results, the experimenter must have knowledge of the constituent ion species of the plasma. The method is applicable only when the plasma is substantially single-specied, with little impurity.

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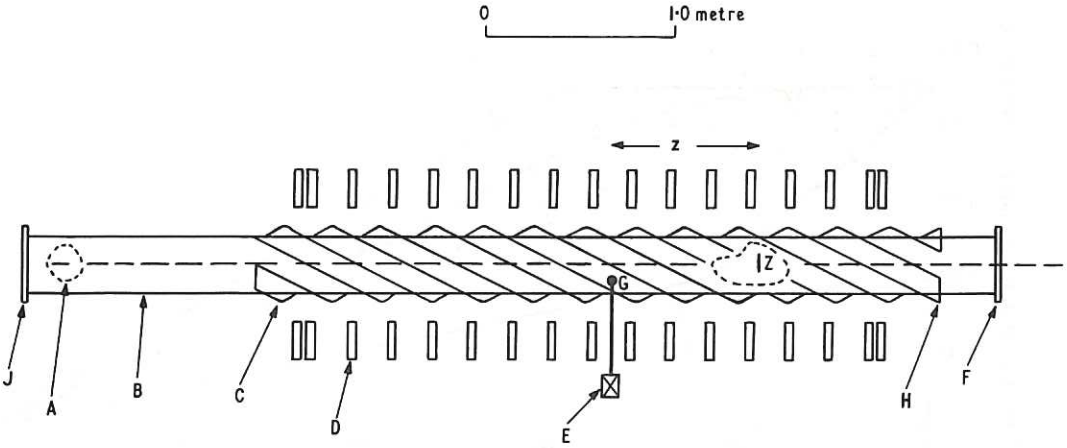

Fig.1 General view of the apparatus. A, 22.5 cm diffusion pump: B, vacuum tube, 30 cm internal diameter: C, helical $\ell = 3$ windings: D, B_z field coils: E and G, the plasma gun and electrodes: F and J, vacuum tube end plates: H, helical-winding current return paths: Z, probe position.

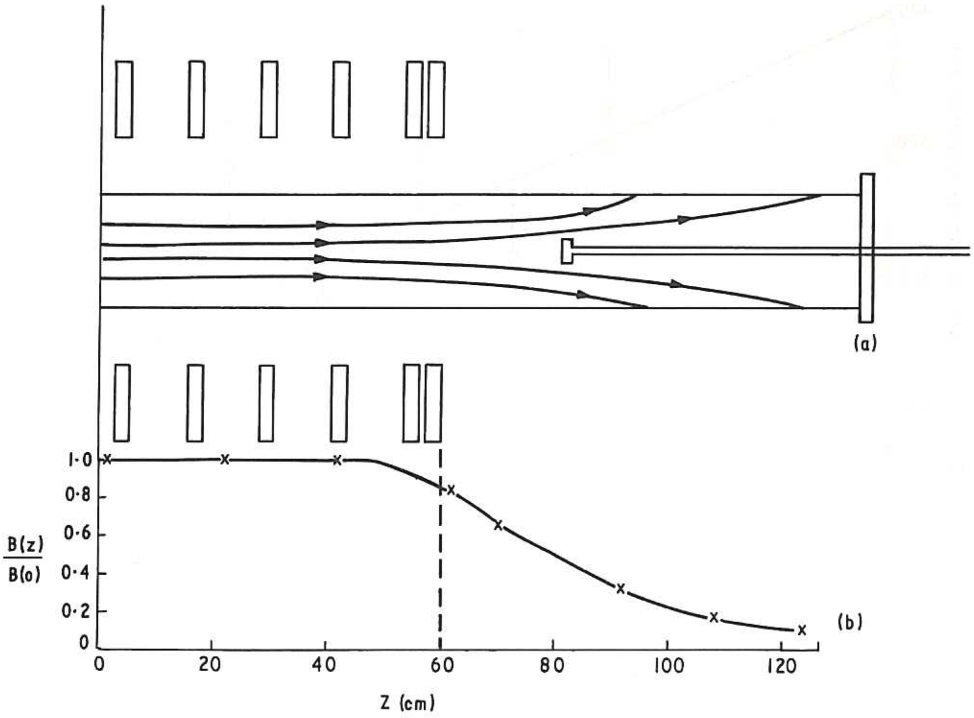

Fig.2 Variation of B_z with axial position Z.

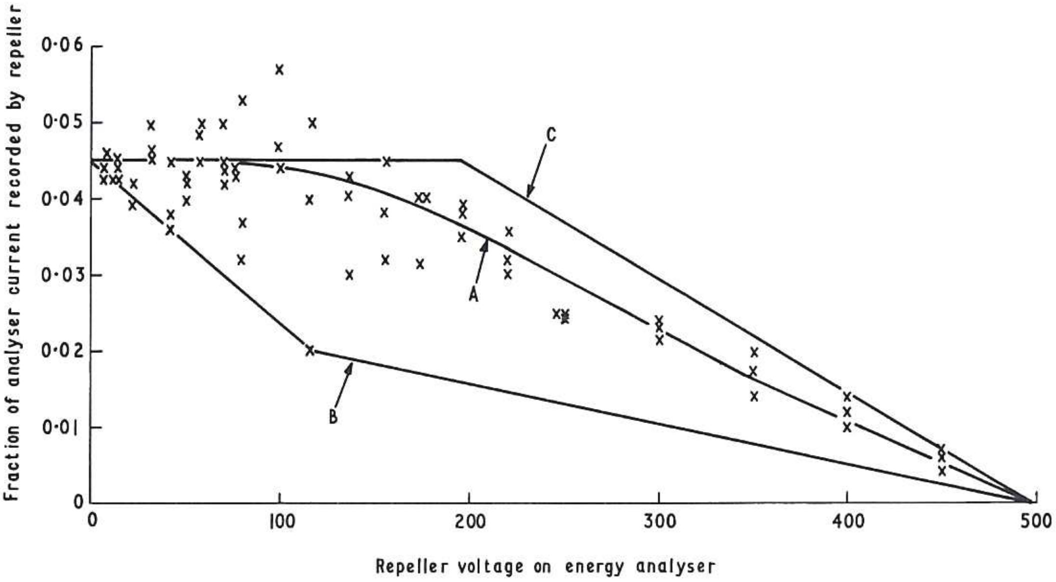

Fig.3 Typical energy analyser result, this one being at a position Z such that $B(z) = \frac{1}{2}B(o)$.

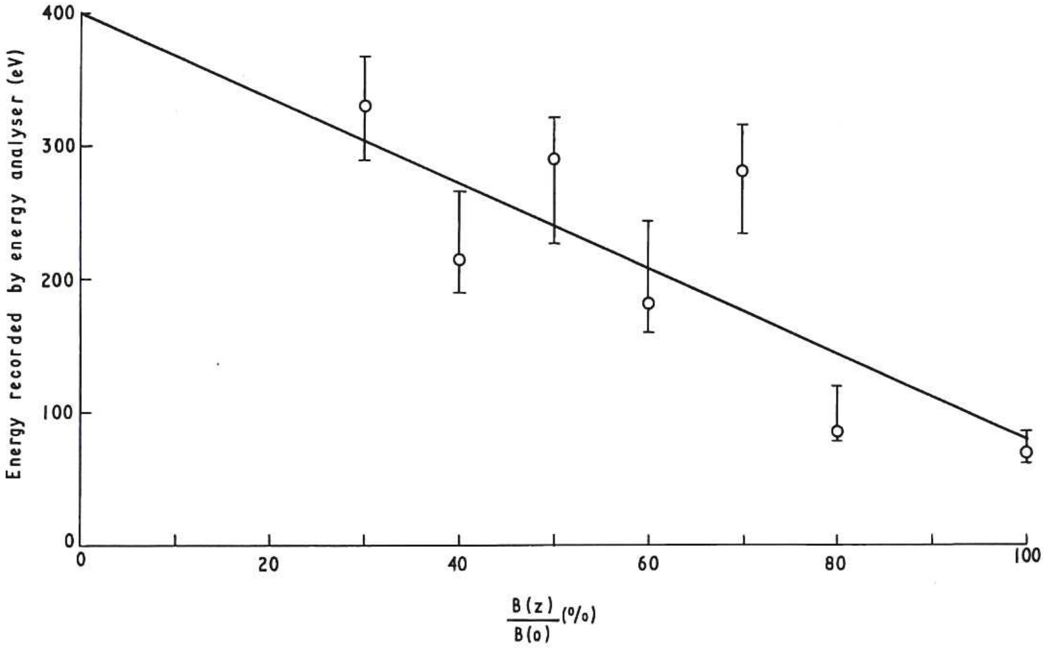

Fig.4 Energy recorded by energy analyser, plotted against B(z)/B(o).

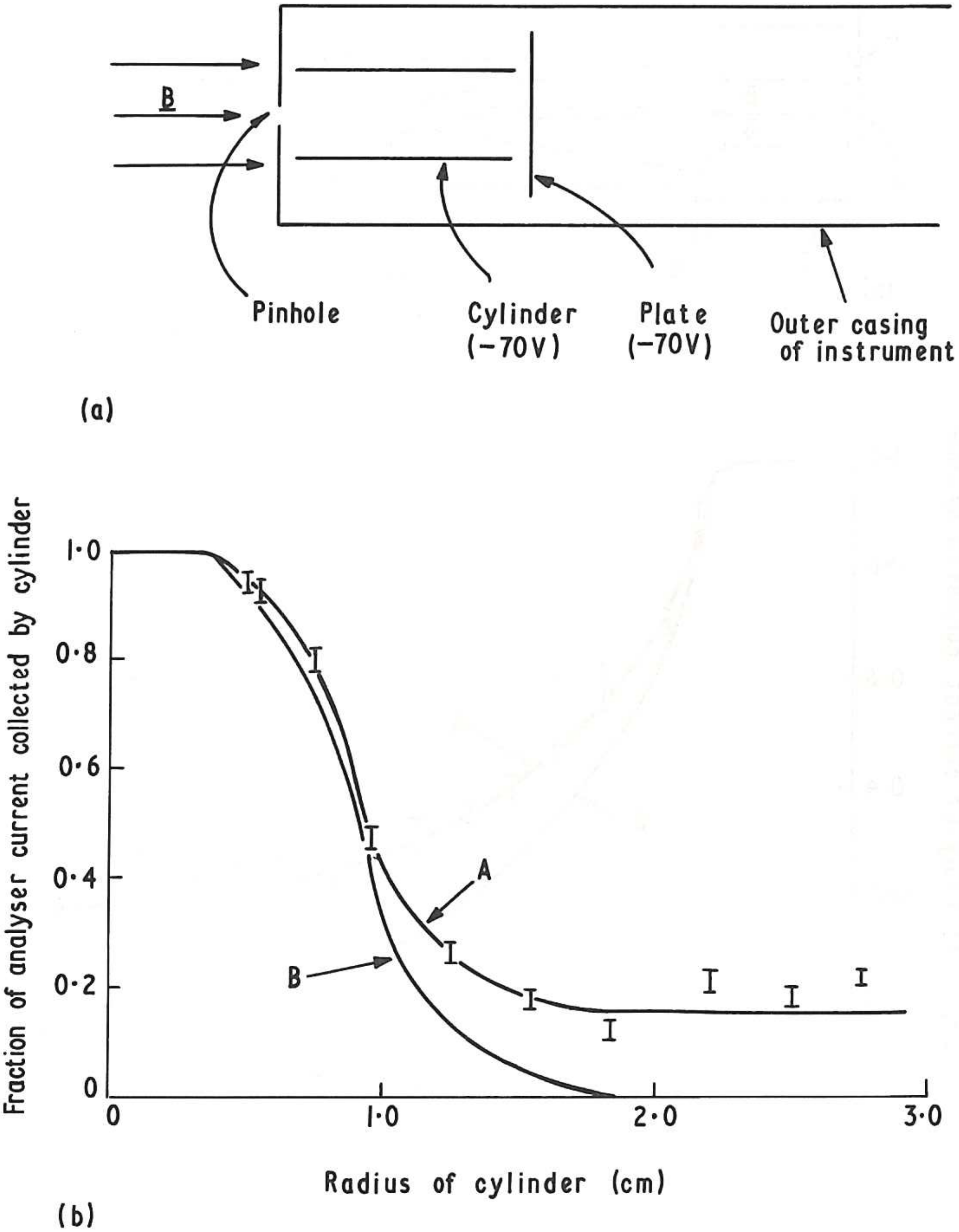

Fig.5 (a) Ion Larmor radius analyser (after Ashby, 1968).
(b) Results obtained with the analyser. Curve (A) is a smooth curve through the experimental points. Curve (B) makes a correction for the supposed impurity of high atomic mass.

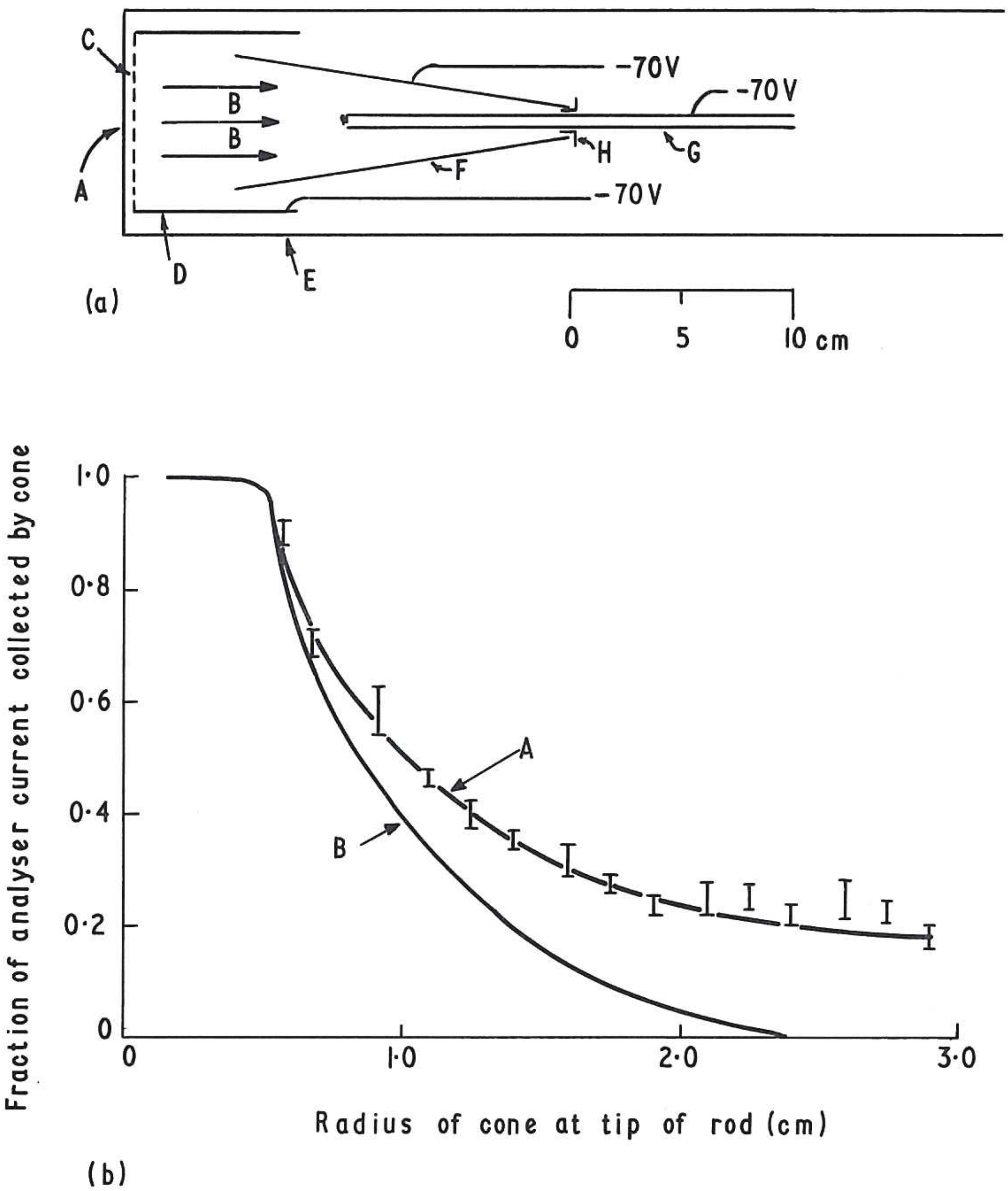

Fig.6 (a) The Conical modification of the Larmor radius analyser. A, pinhole: B, magnetic field: C, 99% transparent grid, mounted on a stainless-steel cylinder D: E, outer casing: F, cone: G, rod: H insulator. (b) Results obtained with the modified analyser.