CLM-P251

United Kingdom Atomic Energy Authority
RESEARCH GROUP

Preprint

THE PRODUCTION OF HIGH CURRENT, HIGH QUALITY BEAMS OF IONS AND NEUTRAL PARTICLES

J. R. COUPLAND
E. THOMPSON

Culham Laboratory
Abingdon Berkshire

1970

CLM-P 251

THE PRODUCTION OF HIGH CURRENT, HIGH QUALITY BEAMS OF IONS AND NEUTRAL PARTICLES

J.R. Coupland and E. Thompson
U.K.A.E.A. Research Group, Culham Laboratory,
Abingdon, Berks.

(To be submitted for publication in Rev. Sci. Instr.)

ABSTRACT

This paper describes results obtained with a hot cathode constricted arc plasma source and a single aperture three electrode accel-decel extraction system.

The energy range covered is 5-25 kilovolts for positive ions and 1.7 - 12.5 kilovolts for neutral beams.

Ion currents of the order of 80 mA H_3^+ and 100 mA He^+ at the higher energies have been obtained through a 3.8 cm diameter aperture at a distance of 180 cm from the source.

The performance as a neutral injector has been evaluated by using the present PHOENIX II experiment.

Finally, the relationship between experiment and theory and the limitations of this type of source, is discussed.

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

September 1970 (ED)

1. INTRODUCTION

In this work the predominant requirement was to produce high intensity beams of hydrogen atoms in the energy range 2 - 15 keV suitable for injection into present and future plasma containment experiments. These beams may be formed either by charge exchange of atomic ions [Ref.1] or by the break-up of molecular ions; (Dissociations and charge exchange) [Ref.2].

Charge exchange of atomic ions has the advantage that the divergence of the H^o beam is essentially that of the incident proton beam, but there remains the difficulty of producing high current proton beams at low energies.

In addition to the possibility of obtaining more than one H^o per incident ion the use of molecular ions enables one to take advantage of the $V^{3/2}$ power law for ion extraction, however this approach results in the introduction of appreciable divergence to the neutral beam at low energies due to the binding energy of the molecular ion.

If θ = maximum half angle of divergence in degrees we have

$$\theta_{max} = 1.81 \sqrt{\frac{\chi}{E}}$$

where χ is the excitation energy per proton in eV and E is the energy of the neutral atom in keV.

The value of χ is determined by the reaction being considered and as shown in refs. 3, 4 may be either 1.2 eV or 3.2 eV per proton for H_2^+. Equivalent results for H_3^+ do not appear to be available but we would not expect the excitation energy per proton to be significantly different.

For immediate application to PHOENIX II [Ref.2] where it was more important to maximise the current rather than minimise the energy it was thought more profitable to produce molecular ions.

In order to be able to produce a wide range of final H^{o} energies we are interested in the yield of both H_2^+ and H_3^+ ions.

2. DESCRIPTION OF APPARATUS

The plasma source and extraction system are shown in Fig.1. It consists of a modified duoplasmatron source [Ref.5] and a single aperture accel-decel extraction system [Ref.6,9]. The modified duoplasmatron type of source was selected purely for convenience. The accel-decel system was designed so that the apertures and spacing of the electrodes could be easily varied by means of metal shims. The insulator between the source and extraction system enabled the source to be operated as a modified PIG discharge or as a magnetically constricted hot cathode arc.

Fig.2A and 2B show the beam line geometries which have been used. All currents were measured with a constant flow water calorimeter using a differential temperature transducer, with digital readout. Electrical measurements of the beam current were approximately twice those obtained using the calorimeter. The effect of electrons formed in the decel gap being accelerated down the axis of the beam and depositing their energy on to the calorimeter was found to be negligible.

The mass selection of the required ion was carried out by means of a magnetic lens. Fig.3 shows typical magnetic field values along the axis of the ion source with the lens energised.

3. EXPERIMENTAL RESULTS

These fall into three sections: operation with helium, operation with hydrogen and finally operation on the PHOENIX II injector.

(1) Operation with Helium

Because of the ease of operation with helium and the simplicity of having only one ion species present (He^{++} was observed to be negligibly small) the effects of systematic variation in extraction geometry were studied using He^+ ions. The results obtained for various values of extraction gap are shown in Fig.4. In addition to measuring the current transmitted through the whole beam line, a 12 cm diameter retractable calorimeter could be placed in front of the first stop enabling the total current transmitted through the lens to be measured and not just that fraction which was accepted by the stop system. These results are also shown in Fig.4.

(2) Operation with Hydrogen

Fig.5 shows the measured focussed current of H_2^+ and H_3^+ ions as a function of extraction energy.

A mass analysis of the beam was made under various conditions using a magnetic analyser which accepted a small section of the beam after it has passed through the end calorimeter. A typical mass spectrum obtained in the absence of magnetic focussing is shown in Fig.6. Mass analysis of a magnetically focussed H_3^+ beam showed that the unfocussed ion species amounted to less than 10% of the total current. However, in the case of focussed H_2^+ it was found that as much as 50% of the beam consisted of H_3^+ and as such, represents a considerable error in the H_2^+ yield shown in Fig.5.

(3) Operation on the PHOENIX II Injector

The source was mounted on the PHOENIX II injector (see Fig.2B for relevant dimensions) and the H^0 yield as a function of energy was measured using $C_8 F_{16}$ and H_2O as the dissociation media - see Fig.7.

4. DISCUSSION OF RESULTS

The optimisation of H_2^+ and H_3^+ is carried out by varying the gas pressure in the discharge; the gas feed required for H_3^+ optimisation is 0.25 litre torr sec^{-1} whereas that for H_2^+ is somewhat lower (0.18 litre torr sec^{-1}). This behaviour is to be expected since the formation of H_3^+ is via the reaction

$$H_2^+ + H_2^o \rightarrow H_3^+ + H^o \qquad [\text{Ref.7}]$$

Operation at higher energies resulted in saturation of the H_3^+ current. This is interpreted as being due to breakup of the H_3^+ ions in the plasma source, which is borne out by the observation that the output of both H_2^+ and H^+ increased as the H_3^+ yield decreased. The results obtained with helium also confirm that the saturation in H_3^+ output is a property of the plasma source and not the extraction system since this phenomena was not observed with He^+. The effect of molecular ion breakup in the dense plasma required to give space charge limited emission from a high current density extraction system may set a limit to the maximum molecular ion current obtainable. Hence in order to obtain large currents of H_3^+ ions it may be necessary to employ systems which have a relatively large area and low current density.

We have compared the results obtained with helium with the theory of space charge flow between concentric spheres which predicts

$$\mu = 14.67 \times 10^{-6} \frac{(1 - \cos \theta)}{(- \alpha)^2}$$

where the perveance μ is defined as $\frac{I}{V^{3/2}}$ amp $volts^{-3/2}$, θ is the semi-angle of convergence and $(- \alpha)^2$ is the Langmuir-Blodgett function [Ref.8]. The above expression applies to electron flow and when discussing the performance of ion sources, the perveance is expressed in terms of an equivalent electron perveance

$$\mu_e = \left(\frac{M}{m}\right)^{\frac{1}{2}} \frac{I}{V^{3/2}} \text{ amp volts}^{-3/2}$$

where M and m are the ion and electron masses respectively. Fig.8 shows the perveance as a function of both extraction energy and extraction gap calculated from the data of Fig.4 (retractable calorimeter). In the case of the calorimeter at 180 cm (end calorimeter) a more appropriate quantity would be current per unit solid angle or beam brightness; but we have shown both on the same scale to indicate the useable current through our geometry (Fig.2B). The agreement between experiment and theory is quite good for large values of extraction gap but the discrepancy increases rapidly as the gap is reduced. Good agreement is not to be expected at these lower values since the extraction gap is now comparable to the hole size and the shape and position of the plasma boundary is somewhat indeterminate. The theory also predicts that the extracted current should be independent of hole size provided that the extraction gap is scaled accordingly. This was observed to be the case except for the smallest extraction aperture used (4 mm), in which case it is probable that the plasma boundary became severely distorted due to the high plasma densities required to give space charge limited emission.

The fall off in perveance at the highest energies which is most marked for the retractable calorimeter is also attributed to distortion of the plasma boundary resulting in the outer edges of the beam being lost.

The major feature of the results on H^o production is that we do not obtain the predicted ratio of $\frac{H^o}{H_3^+} \approx 2.7$ for H_2O and 2.1 for $C_8 F_{16}$. This is due to the very restrictive injector geometry (3° angular acceptance) not being able to accept the additional divergence introduced by the excitation energy of the molecular ions. We found that it was possible to approach the predicted ratio of $\frac{H^{o}}{H_3^+}$ by reducing the beam current, this presumably reduces the emittance of the ion beam which no longer fills the defining stop so that the injector will then be able to accept some additional divergence. (Recent measurements of beam emittance confirm this hypothesis.)

The major limitation of our present work is the plasma source. Any slight misalignment (~ 1 mm) of the plasma source with respect to the extraction system results in severe deflection of the extracted beam and in its present form it is incapable of being used to illuminate a multiple hole extraction system (as for example demonstrated by Hamilton et al. Ref.9). Future work will be aimed at producing a suitable source for a multi-aperture extraction system and the measurement of source emittance.

5. ACKNOWLEDGEMENTS

The authors wish to thank Mr. D.P. Hammond for the many helpful suggestions during the course of this work and also Mr. F. Watters for his valuable assistance in carrying out the experiments.

6. REFERENCES

1. F.G. Gordon and C.C. Damm, Rev. Sci. Instruments, 34, 9 (1963).
2. D.P. Hammond and D.R. Sweetman, 4th Symposium on Engineering Problems in Thermonuclear Research at Frascati, May (1966).
3. H.S.W. Massey and E.H.S. Burhop, Electronic and Ionic Impact Phenomena, p.513, Oxford: Clarendon Press (1952).
4. G.W. McClure, Phys. Rev. vol.40, no.3A, Nov.(1965).
5. G.G. Kelley., N.H. Lazer, O.B. Morgan. Nuc. Instr. and Methods 10, 263 (1961).
6. E.R. Harrison, Journal of Applied Physics, 29, 6 June (1958).
7. D.W. Vance and T.L. Bailey, Journal of Chemical Physics, 44, 2, January (1966).
8. I. Langmuir and K.R. Blodgett, Phys. Rev. 24, 49 (1924).
9. G.W. Hamilton, J.L. Hilton and J.S. Luce. Plasma Physics, 10, pp.687-697, Pergamon Press (1968).

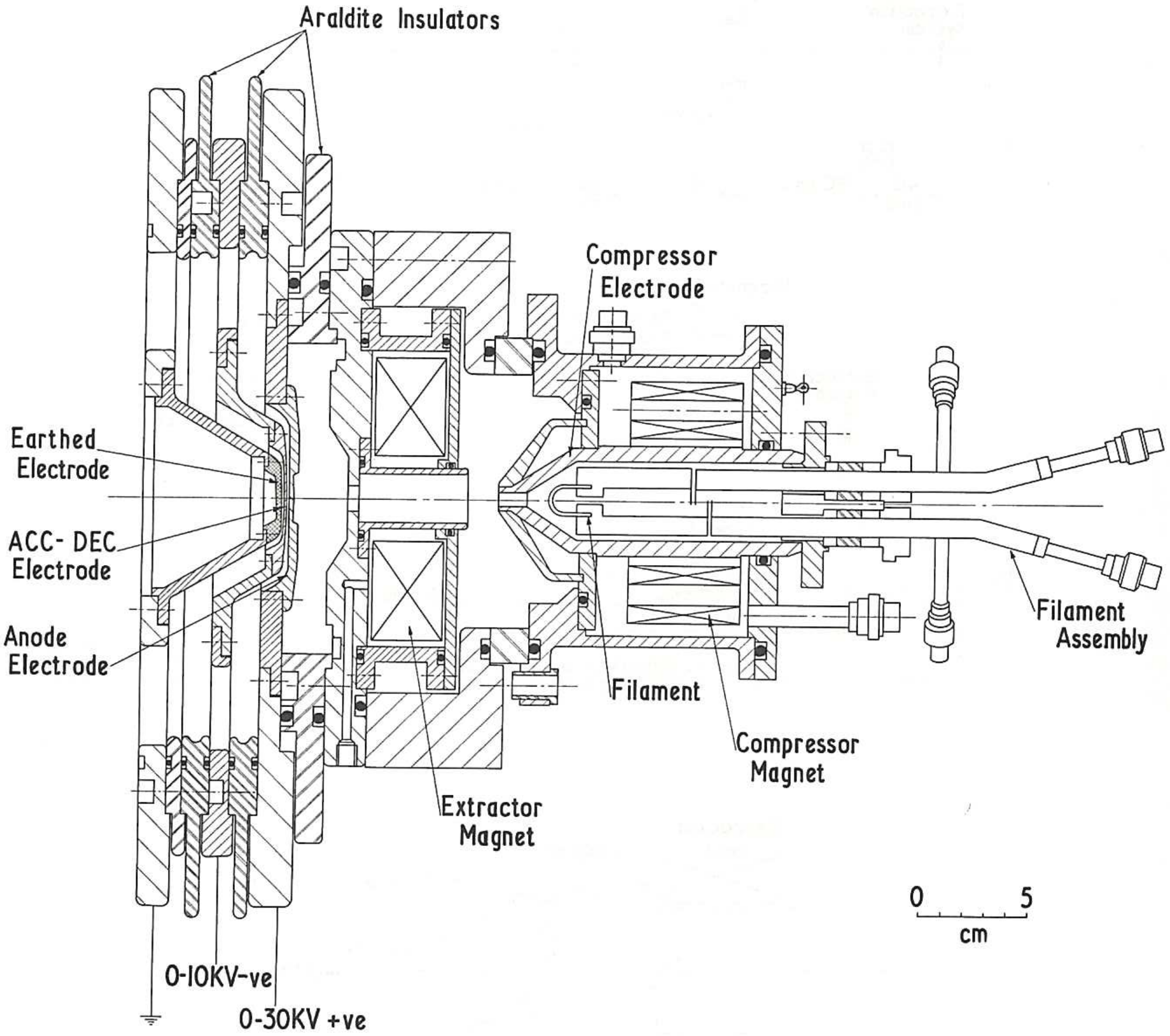

Fig.1 Schematic diagram of ion source and extraction system. The relatively long arc results in a high yield of H_3^+.

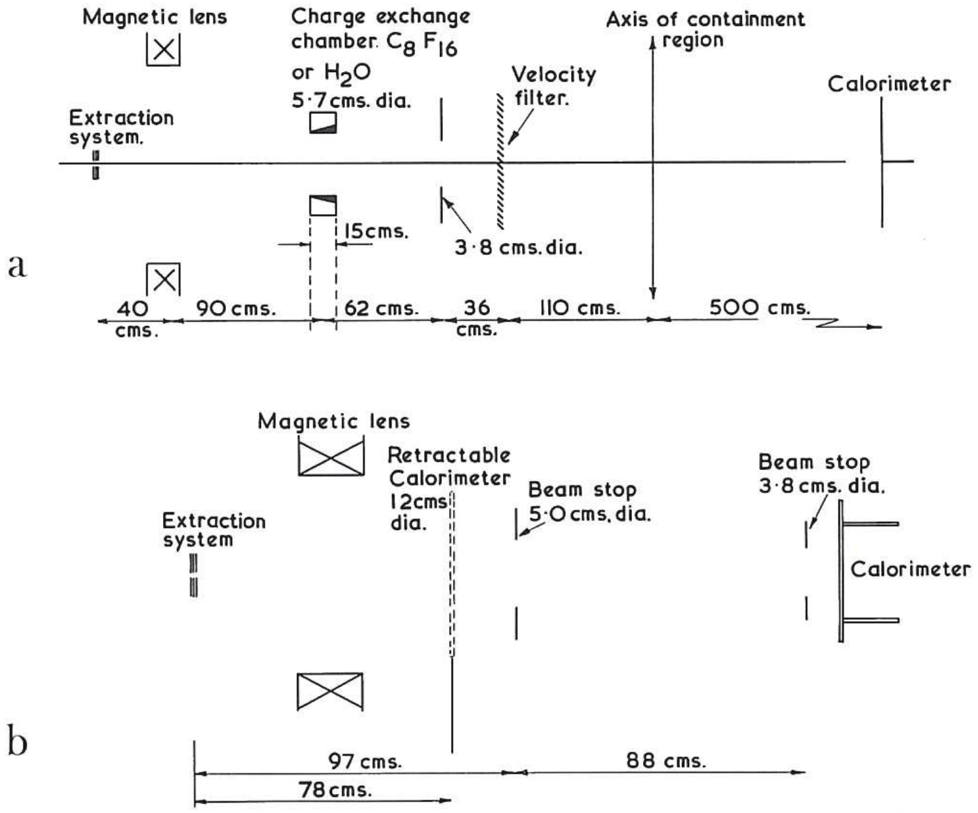

Fig.2 a. PHOENIX II beam line geometry.
b. Test rig beam line geometry.

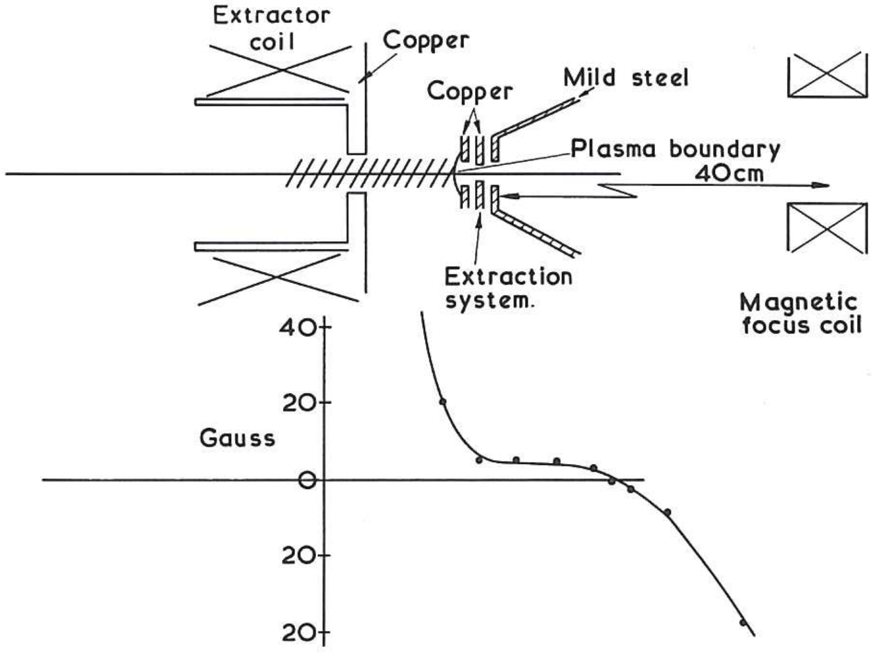

Fig.3 Magnetic field along axis of source and extraction system with magnetic focus coil energised.

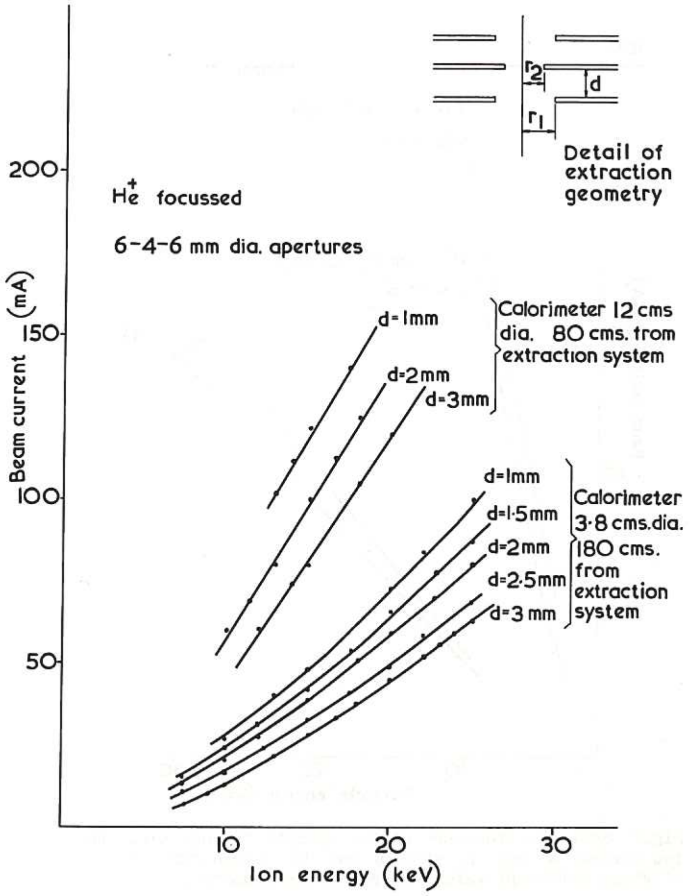

Fig.4 Variation of extracted He^+ current vs. energy for different values of extraction gap.

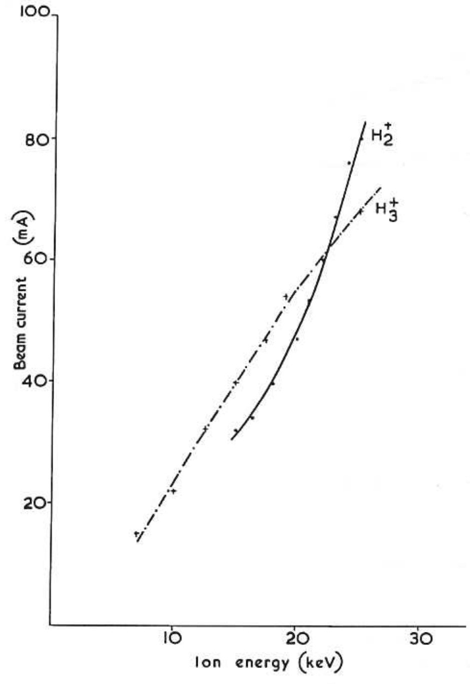

Fig.5 Molecular ion current transmitted through the complete stop system as a function of energy. Data obtained using 6-4-6 mm diameter apertures and 2mm gap in extraction system.

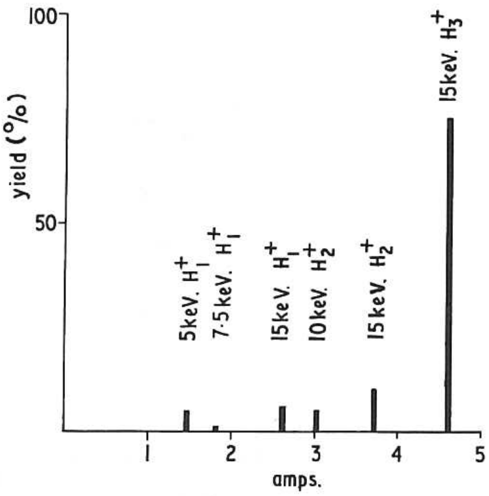

Fig.6 Mass spectrum of 15 keV ion beam in the absence of magnetic focussing.

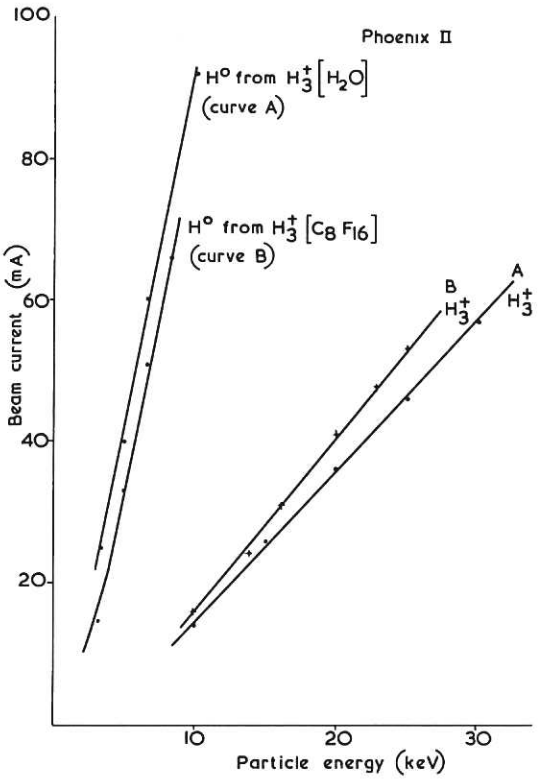

Fig.7 Source performance on the PHOENIX II injector. The two curves A and B showing the H_3^+ yield refer to slightly different values of ectractor geometry.

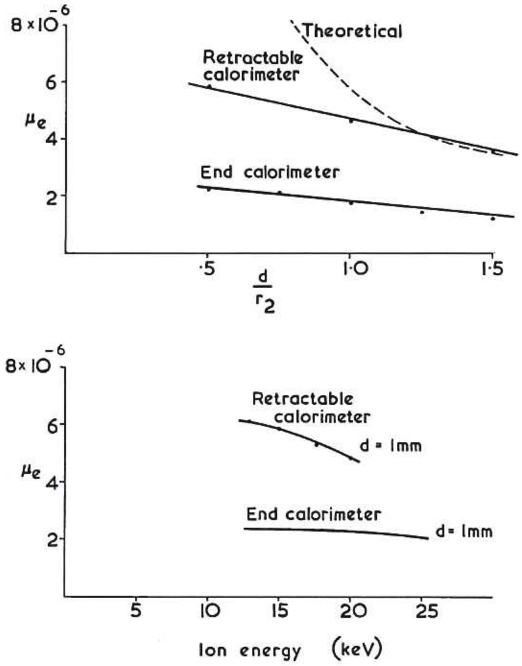

Fig.8 The experimental and theoretical value of equivalent electron perveance as a function of both extraction energy and extraction gap.