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A COMPACT ION SOURCE WITH HIGH BRIGHTNESS

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ABSTRACT

A compact ion source is described with a beam brightness of 9.10^{10} mA/cm^2/steradian which can operate continuously at 50 kV giving a beam current density of up to 110 mA/cm^2. This source has a proton yield of over 55% and has been designed as a pre-injector for use in particle accelerators or meson facilities. Without changing the design, except for the extraction apertures, it could produce a multiple aperture beam of up to two amperes.

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1. INTRODUCTION

High brightness ion beams are of great importance as pre-injectors for particle accelerators and also in providing diagnostic neutral atom beams in the field of controlled thermonuclear research. In this paper we describe an ion source which is very suitable for both these and possibly other applications. The design specification for this source is continuous operation with 50 keV maximum beam energy, a normalised emittance of less than 0.2 millirad mm and a beam current of 40 mA of which 60% must be protons. This source is being incorporated into the pre-injector of the meson facility at the Schweizerische Institut für Nuklearforschung (S.I.N.)[6]. The complete assembly as supplied to S.I.N. consists of three basic components; a plasma source, an electrostatic ion extraction system and a bellows unit to align the beam.

In the following sections, we describe in detail the plasma source and extraction systems, both of which have been developed in the Culham Laboratory as part of an on-going research programme on the production of intense ion beams for applications on controlled thermonuclear research.

2. THE PLASMA SOURCE

The plasma source used to provide the extraction system with the required flux of ions is a small version of the "bucket" or magnetic multipole source developed by Hemsworth[3], and Goede and Green[1]. The high order magnetic multipole which surrounds the anode of this source as shown in Figure 1 confers several major advantages. These are:

(a) High electrical efficiency in ion production

(b) Operation at low pressure

(c) Large volume of quiescent plasma .

The first two advantages are due to the good confinement of the primary ionising electrons emitted by the directly heated tantalum cathodes. The final advantage is particularly significant for high current multi-aperture sources and is due to the exponential decrease of the magnetic field giving a large volume of field free plasma which has uniform density.

The extraction plane, which cannot be magnetically shielded, is either connected to cathode potential or allowed to operate at floating potential. Only one of the four filaments is required to sustain the discharge, the other three being spares.

Although this plasma source is used to illuminate only a single aperture, it would, without further modification, illuminate uniformly a 30cm^2 area to give a total ion current two to three amps of mixed species hydrogen ions.

2.1 The Arc Discharge

The volt-current characteristic of this type of plasma source is a function of the ratio of effective anode (magnetic cusp) area to cathode area and cathode temperature. The characteristic of this source for two values of heater current (which controls the cathode temperature) is shown in Figure 2. Also shown are the characteristics predicted by the theoretical model of the bucket source which has been recently developed by Holmes[(4)] which is based on the source geometry and the field strength of the magnetic cusps.

This model, in which the plasma potential is assumed to be negative with respect to the anode (due to the small anode area), also predicts the electrical efficiency of the plasma source. This ionising efficiency is defined as the ratio of the total ion current to the electrical power supplied to the primary electrons and is the upper curve in Figure 3. Also shown in the lower curve is the total electrical efficiency which is the ion current divided by the total power supplied to the discharge. The agreement between theory and experiment is good and it can also be seen that the arc power needed to produce a high current density is low.

The good confinement of primary electrons is further demonstrated in Figure 4, where we show the ratio of emission to ion current as a function of the reciprocal of the pressure. The slope of this curve can be shown[(2)] to be proportional to the electron confinement time which for this data is 0.26 micro-seconds.

2.2 Ion Species

As is well known, operation of an ion source in hydrogen produces H^+, H_2^+ and H_3^+ ions. By scanning the beam across a small entrance aperture to a magnetic analyser we find the beam profiles for the three species differ as shown in Figure 5. Since we have previously demonstrated[5] that the ion beam produced by our extraction system is emittance dominated (the gross beam divergence scaling as (beam energy)$^{-\frac{1}{2}}$) we interpret the differing profiles as being due to the various ions having different temperatures. It is not unreasonable to suppose that the protons have the highest temperature because they result from dissociative collisions. Since a high proton content implies high value of $n_e\tau_i$, where n_e is the electron density in the source and τ_i the ion lifetime, the protons and/or the parent H_2^+ ions can be heated by ion electron collisions.

By integrating under curves such as those shown, we obtain the data shown in Figure 6 where we display the functional dependence of species yield with extracted current density, j_+. As has been observed on other sources, the H_3^+ content predominates at low values of j_+ whereas the H^+ ion is the major component at high j_+.

The variation of species yield with source pressure is shown in Figure 7 where the main effect is the variation of the ratio of H_2^+ to H_3^+; the H^+ fraction being relatively constant. This enhancement of the H_3^+ yield is due to the high cross-section for the reaction

$$H_2^+ + H_2 \rightarrow H_3^+ + H^o$$

3. THE EXTRACTION SYSTEM

The main advantage of a four electrode extraction system over the more usual three electrode systems lies in the virtual elimination of aberrations and the better control over the beam envelope during acceleration. Aberrations can arise from several sources, in particular the anode hole effect, plasma boundary curvature and the beam forming electrode profile.

The anode hole effect relates the extraction aperture diameter to the extraction gap. The presence of the field in the second gap in the tetrode extraction system allows considerably larger extraction apertures than in a comparable triode structure. The difference in electric field between the first and second gaps creates an additional lens at the second or intermediate electrode which allows the plasma boundary to be nearly flat. This reduces considerably spherical aberration compared to that in a triode extraction system. This flat plasma boundary simplifies the shape of the correct Pierce profile for the first electrode (8) again reducing aberrations and allowing a uniform current density to be extracted over the entire aperture.

If a collimated beam is required at the exit of the beam formation and acceleration structure then the use of a tetrode system can considerably reduce the degree of initial compression required to focus the beam. This compression arises from diverging lens action of the aperture in the final acceleration electrode which also suppresses the electron from the beam plasma. Hence the beam diameter is increased after extraction and this improves the degree of space charge neutralisation of the drifting beam as this is critically dependent on the beam radius (5). Thus, the overall residual beam divergence is considerably lower in tetrode extraction systems.

3.1 The Extracted Ion Beam

The specified proton yield of 60% requires a high total current density as seen in Figure 6, which, together with the specified beam current of 40mA, determines the extraction aperture diameter to be 7 millimetres. The beam energy of 50keV allows the rest of the extraction geometry to be derived and this is shown in Figure 1.

It should be noted that this first aperture could be increased to ∿12mm diameter with a corresponding increase in total beam current.

The extracted current density, obtained from calorimetric measurements of the total beam current, is shown in Figure 8 as a function of the extraction voltage. The functional dependence is greater than the expected $V^{3/2}$ variation due to the changing ion species. Using the measured species variation we also show in Figure 8, the proton current density as a function of beam energy. Measurements on similar extraction systems with He^+ beams confirm a $V^{3/2}$ dependence.

3.2 Beam Envelope

The radial power profile of the beam was measured using a 3mm diameter calorimeter 1.2m from the extraction system for two typical values of beam energy. As shown in Figure 9, the beam profile is very close to a true Gaussian.

The emittance diagram of the beam is shown in Figure 10. The shape of the diagram clearly shows that the aberrations are very small. The reduction in the width of the diagram at a radius of 9 mm suggests that there are two diagrams of differing temperatures, which is in agreement with the measured spatial variation of the various ion species (Figure 5).

The normalised area at the 1/e intensity contour is 0.11π mm millirad and at the 10% contour the area is 0.19π mm millirad. The area within the 1/e contour is related to the ion temperature by the expression

$$\varepsilon_n = T_i^{\frac{1}{2}} \left(\frac{2e}{m_i}\right)^{\frac{1}{2}} \frac{4e}{\pi c}$$

where ε_n is the normalised area, ρ is the aperture radius and c is the velocity of light. Using this expression, T_i is 0.57 eV. The normalised beam brightness of the 40 keV beam can be evaluated from ε_n and is $9.1\ 10^{10}$ mA/cm^2/steradian for a proton beam. This is considerably higher than other ion sources [7]. greater brightness can be obtained by modifying the extraction geometry to obtain $.10^{12}$ mA/cm^2/ steradian at 60 kV, which is the highest so far obtained in hydrogen. The measurements of beam emittance have been made over a long period of time, including one period of eight hours of continuous d.c. operation, without any observable deterioration of beam quality or brightness. In addition, no systematic changes in any other parameters of the plasma source or beam have been observed during this period.

CONCLUSION

The ion source described here has been shown to give a high brightness beam which can be operated continuously for long periods at high current densities. This source is well suited as a pre-injector for accelerators (its present use), or alternatively it can extract an ion beam which can be used as a diagnostic in magnetically confined plasmas. Increasing the beam current to 150 mA in a single aperture beam (or 2 amps in a multi-aperture array) and an increase in beam energy to 60 - 70 keV appear to be entirely within the capability of the design.

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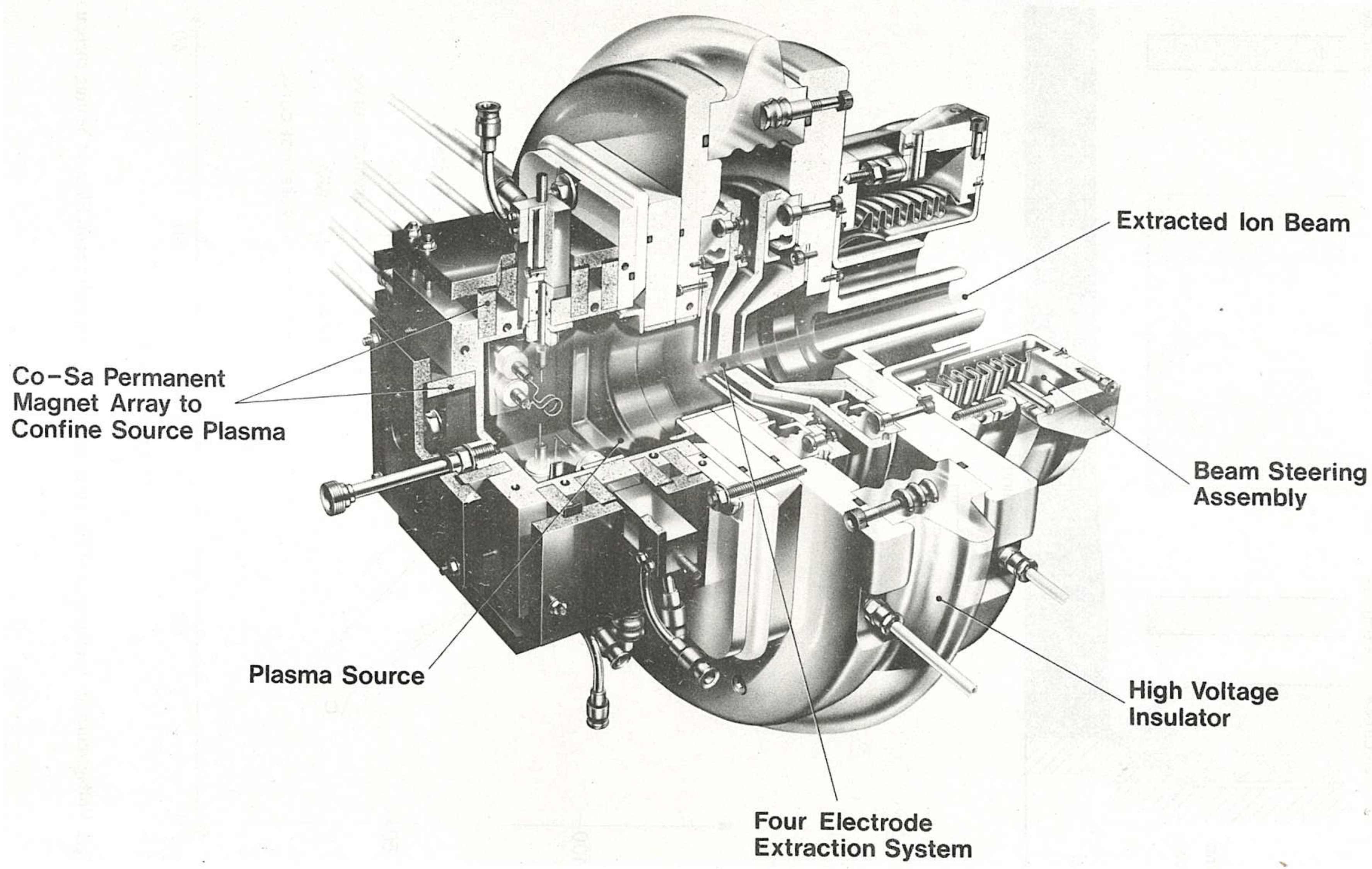

Fig.1a Cut-away view of the ion source.

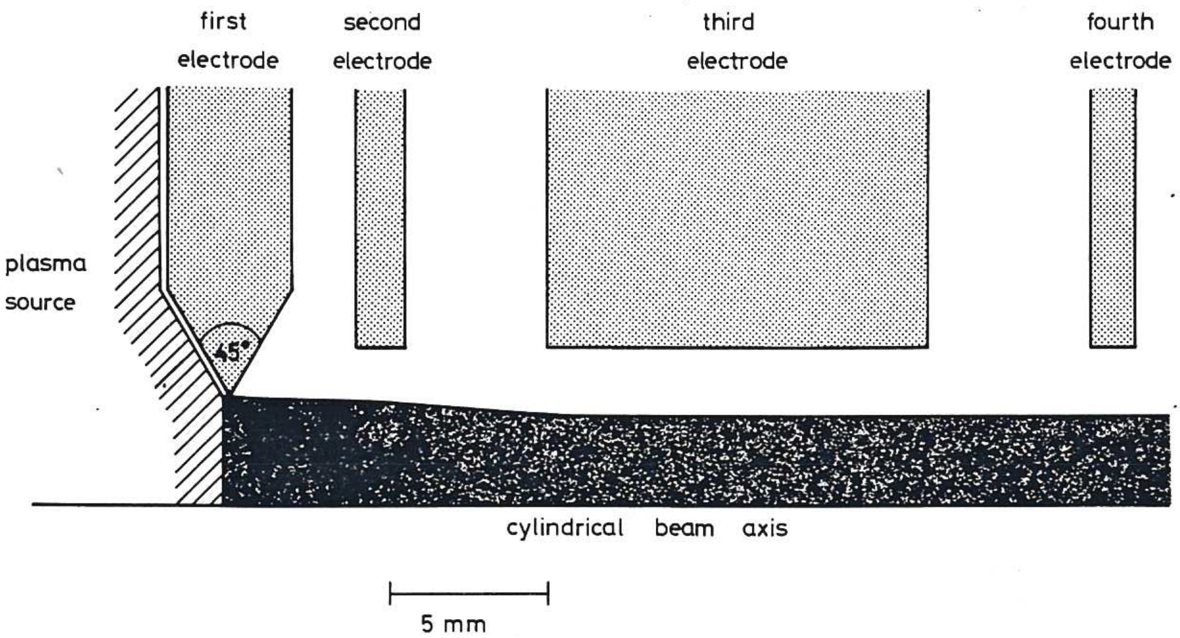

Fig.1b Cross-section of extraction system.

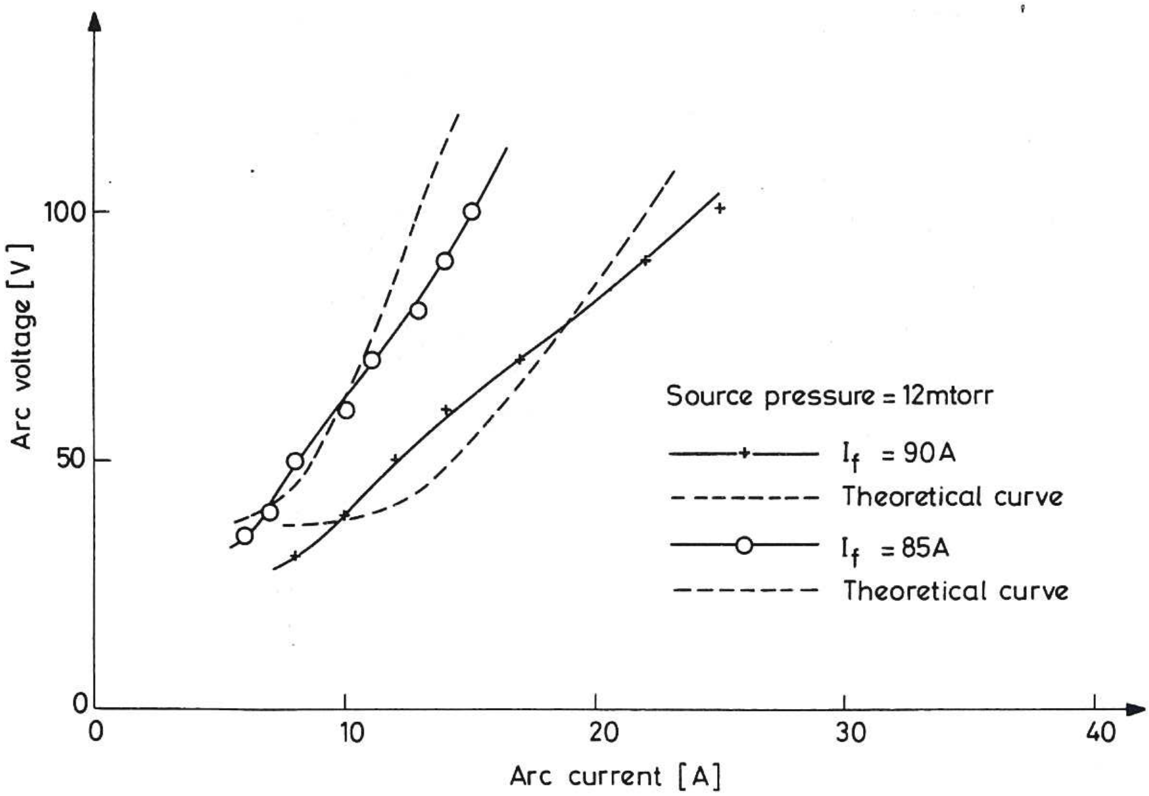

Fig.2 Voltage-current characteristic of the ion source showing dependence on filament heating current.

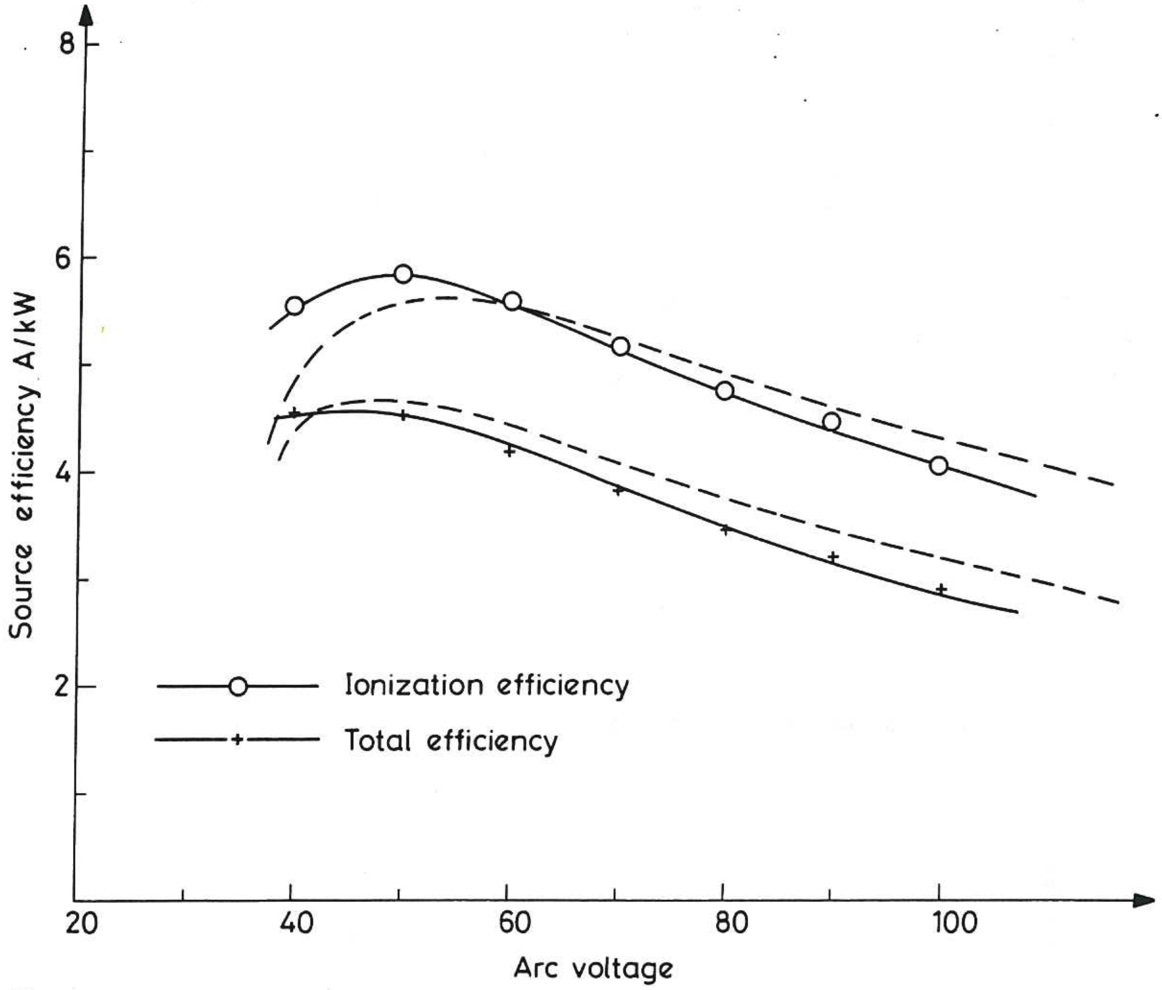

Fig.3 The dependence of the ionisation efficiency, I_+/I_eV_a and total efficiency, $I_+/V_a(I_e + I_+)$ on the arc voltage. The arc should be operated around the maximum of these curves.

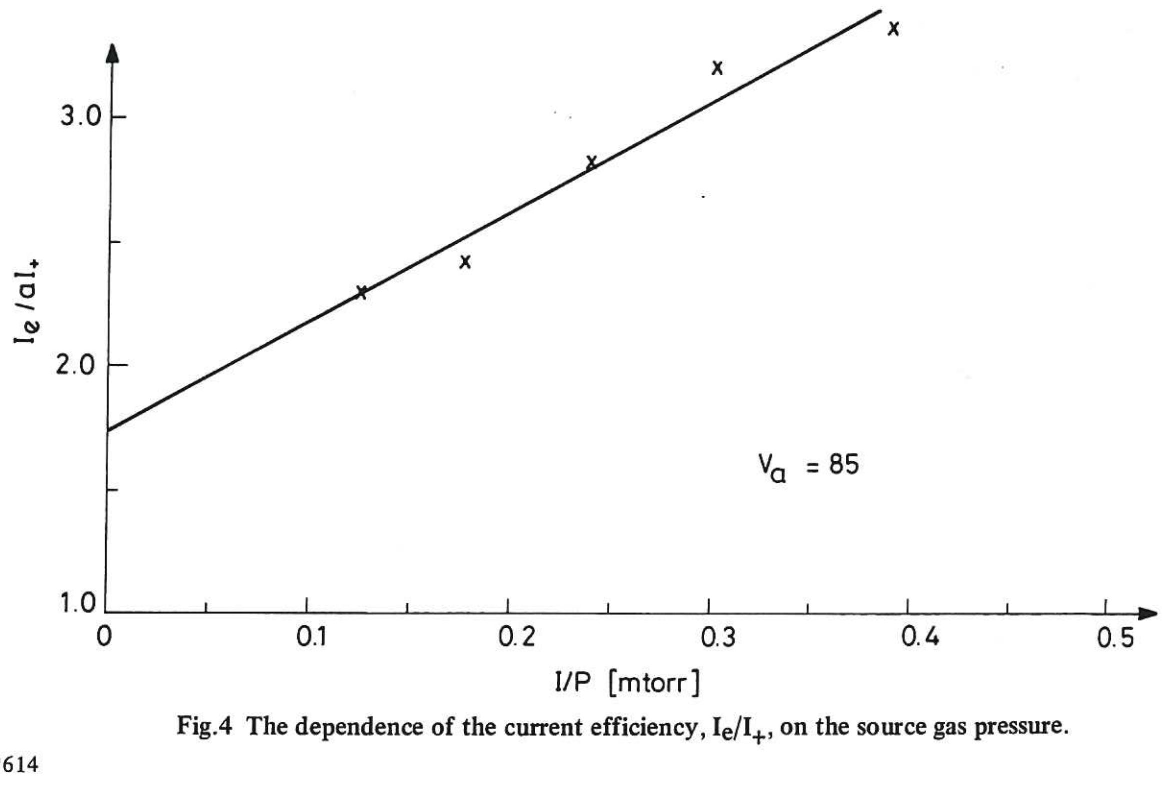

Fig.4 The dependence of the current efficiency, I_e/I_+, on the source gas pressure.

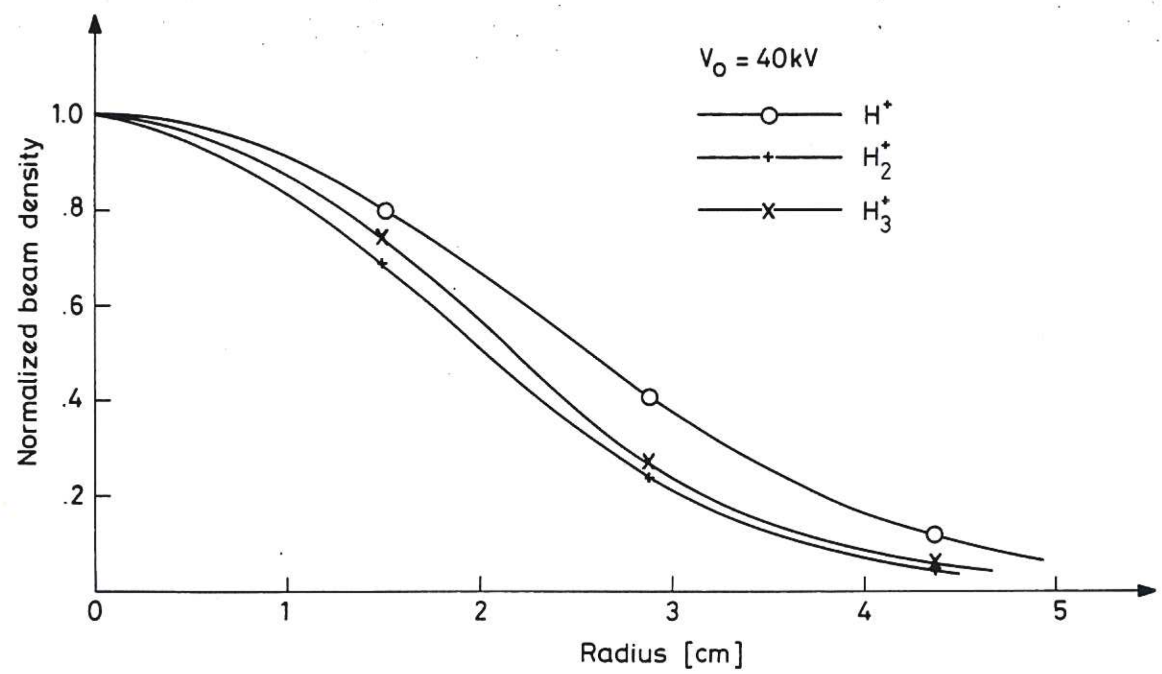

Fig.5 The shape of the beam profile for each of the three primary ion species.

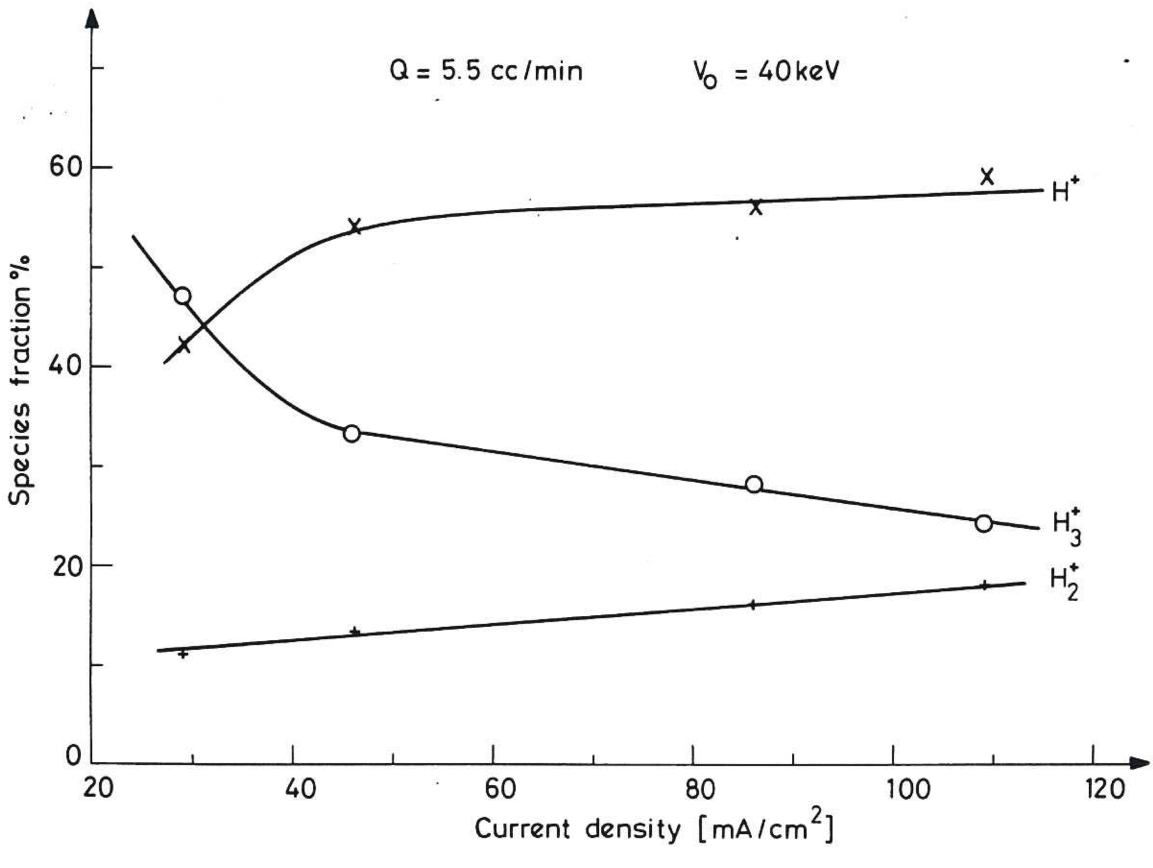

Fig.6 The dependence of the three hydrogen ion species on plasma current density.

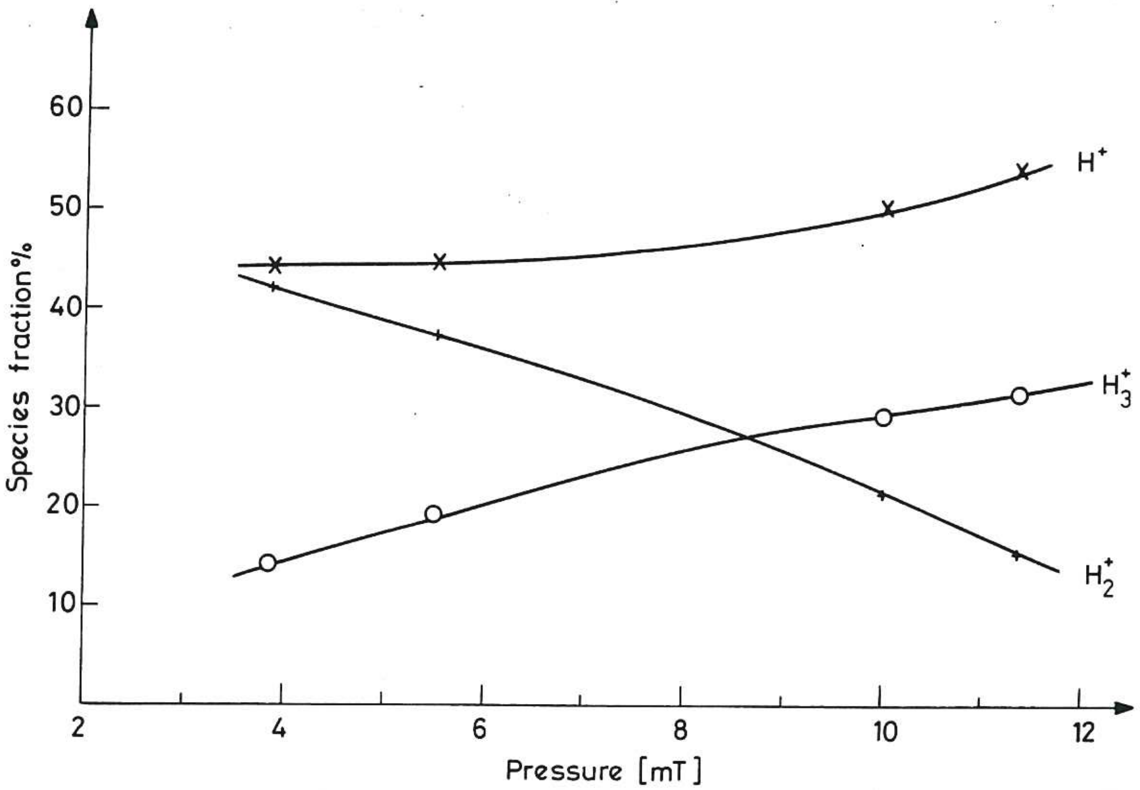

Fig.7 The dependence of the three hydrogen ion species on the source gas pressure.

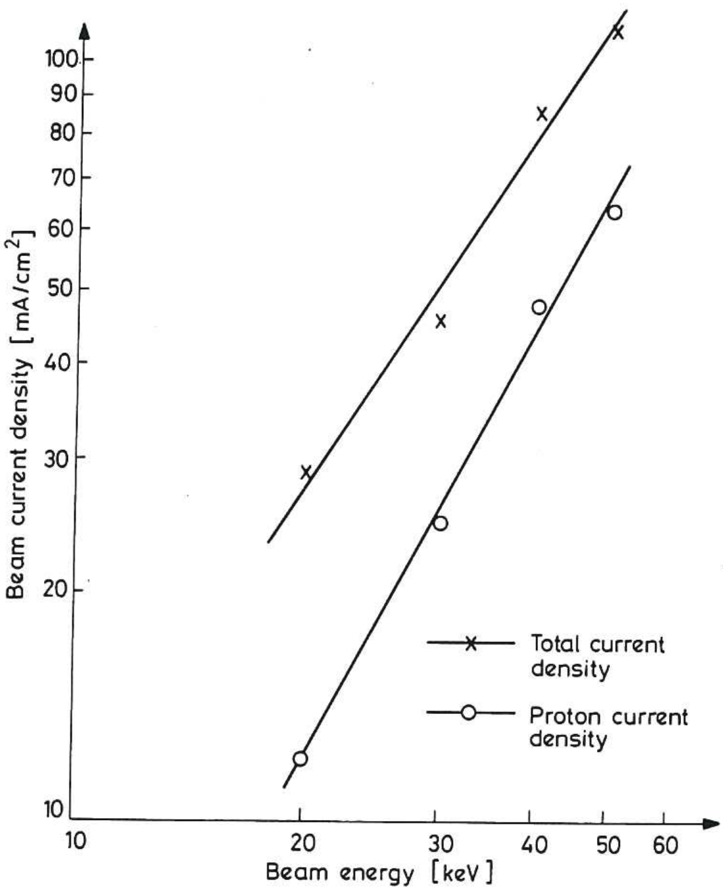

Fig.8 The total beam current density and the fractional proton current density dependence on beam energy.

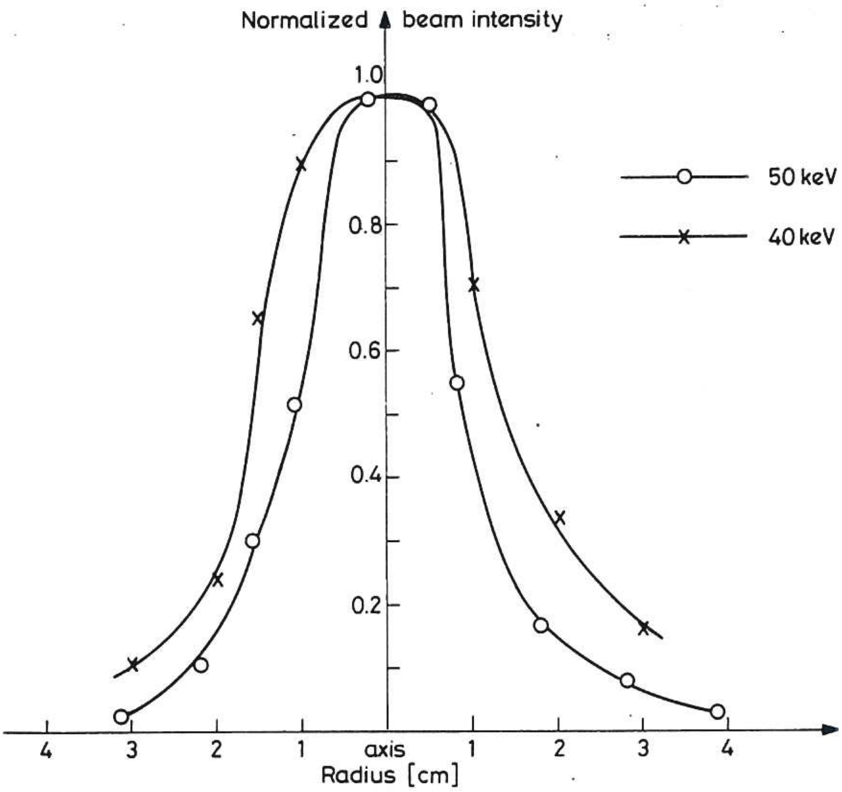

Fig.9 Beam profile at 1·2 m from the extraction aperture measured with a scanning calorimeter.

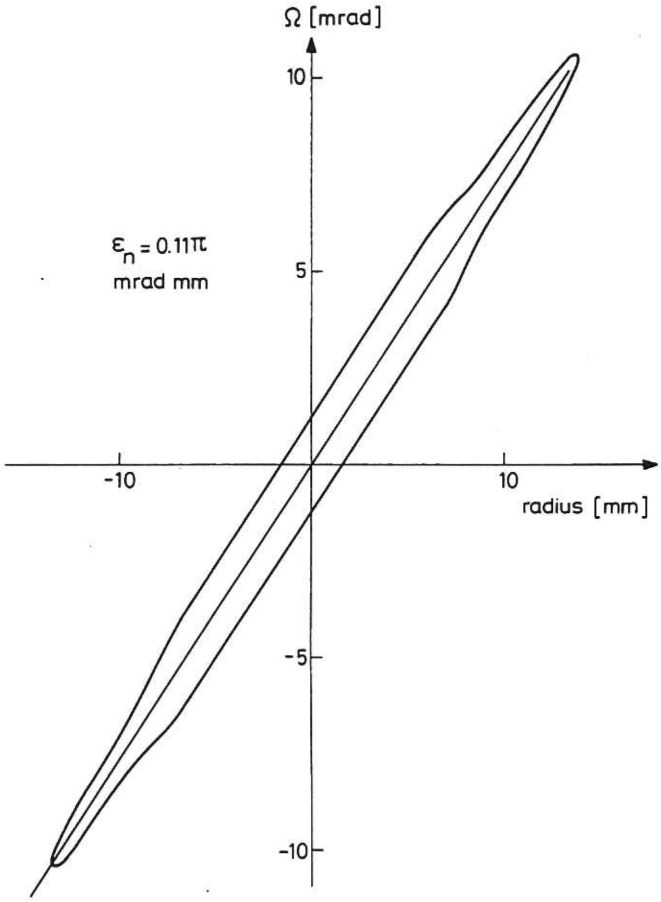

Fig.10 Beam emittance envelope at $^1/_e$ of maximum intensity. The reduction in width at r = 8 mm suggests that there are two ion temperatures.