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Abstract

Internal magnetic structures or filters, which enhance the proton yield in magnetic multipole sources, also modify the electron temperature near the ion extraction electrodes. Results are presented for an electromagnetic filter which reduces the electron temperature by up to a factor of four. These measurements are in close agreement with a theoretical model based on the classical diffusion of particles and energy through the magnetic field of the filter.

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INTRODUCTION

Recently, magnetic multipole, or bucket, sources have been developed by Ehlers and Leung[1] with internal magnetic field structures with the aim of increasing the proton fraction extracted from the source. Such structures are called magnetic filters because they divide the usual single field free volume existing in normal multipole sources into two field free volumes separated by a thin sheet of magnetic field. This magnetic filter impedes the flow of electrons from the plasma production volume (where the electron emitting filaments are located) to the extraction volume next to the ion beam accelerating electrodes. Holmes[2] has shown that the flow of electrons through this magnetic filter obeys classical diffusion scaling based on coulomb collisions.

It has also been observed experimentally that the magnetic filter, in addition to impeding the electron flow, also reduces the plasma electron temperature in the extraction volume relative to that in the production volume. In this paper we report on the experimental data from the dependence of this change of temperature in a hydrogen discharge as a function of magnetic field and arc current and also present a theoretical model to explain this phenomenon.

2. Experimental Results

2.1 The source

The magnetic multipole or bucket source used in these experiments is shown in Fig. 1. The plasma production volume contains the electron emitting filaments and is separated from the extraction volume by the magnetic filter which is formed by a special solenoid. This coil creates a magnetic field whose spatial intensity has an approximately gaussian dependence, as shown in reference 2. The maximum flux that can be formed is about 400 gauss cm. The vacuum wall is the anode of the discharge and is covered by lines of permanent magnets. The multipole field produced by these magnets contains the plasma and only allows the electrons to reach the anode at the field cusps.

The base of the discharge volume has no magnetic shielding and forms the extraction electrode which can be biased to any potential relative to the anode. In this experiment it is biased negative to the anode to confine the electrons in the plasma. The source also contains two single Langmuir probes, one in each volume, to measure the plasma density and electron temperature.

2.2 Electron temperature and plasma density measurements

In Fig. 2 are shown some of the Langmuir probe characteristics obtained in the extraction volume as the magnetic field is varied. The reduction in electron temperature at high fields can be seen clearly. Fig. 3 shows explicitly the dependence of T_0, the production volume temperature, and T_1, the extraction volume temperature, as a function of the magnetic flux at constant arc current. The value of T_0 is approximately constant, but T_1 decreases rapidly at low fields tending to a low limit at high fields. In Fig. 4 the dependence of the plasma densities on each side of the filter (n_0 and n_1) is shown as a function of the filter field. We observe that n_1 is approximately constant, but n_0 increases with the magnetic flux.

When the magnetic flux is held constant at 300 gauss cm and the discharge current is varied we obtain the results shown in Figs. 5 and 6. In Fig. 5 a gradual increase in both T_0 and T_1 is observed with increasing discharge current. Fig. 6 shows that the density on both sides of the filter rises almost linearly with the discharge current.

In a recent measurement by Pincosy[3] using a permanent magnet filter of 110 gauss cm, a ratio of T_1/T_0 of 0.55 was obtained when n_0/n_1 was about 1.6 (n_1 corresponded to a positive ion current density of 450 mA/cm^2 near the filter).

3. Theoretical Model

In any system where particles collide with fixed scattering centres, the thermal conductivity, Λ, arising from this scattering process is related to the diffusion coefficient, D, by the equation:

$$\Lambda = cnD \tag{1}$$

where n is the scattering centre density and c is the specific heat per scattered particle. The ensemble formed by these scattered particles is a Lorentzian gas and in this particular instance we assume it to have three degrees of freedom; hence

$$c = 3\,k/2 \tag{2}$$

where k is Boltzmann's constant.

It has been shown by Holmes[2] that the electrons diffuse across the filter due to coulomb collisions with the plasma ions. However, the ions are essentially unmagnetised; their role is that of fixed scattering centres for the electrons[2].

From Equation 1 we obtain:

$$\Lambda_{\perp} = \frac{3k}{2} n_i D_{\perp} \tag{3}$$

where n_i is the ion density and $D_{\perp}$ is electron diffusion coefficient for flow perpendicular to the transverse magnetic field. This flow is hence parallel to the axis of the plasma source in Fig. 1.

The flow of heat along this axis per unit area is hence:

$$Q_{\perp} = - \Lambda_{\perp} \frac{dT}{dz} \tag{4}$$

In parallel with this heat flow there is a corresponding current density, $j_{\perp}$, of plasma electrons. Holmes[2] has shown that in this experimental situation there is negligible electric field and virtually no lateral loss (i.e. parallel to B) of particles, hence:

$$\frac{j_{\perp}}{e} = - D_{\perp} \frac{dn_e}{dz} \tag{5}$$

Since n_e is equal to n_i everywhere, we can reduce Equations 3, 4 and 5 to

$$\frac{dT}{dz} = \frac{2eQ_{\perp}}{3kj_{\perp}} \cdot \frac{1}{n_e} \frac{dn_e}{dz}$$

which integrates to give:

$$T_0 - T_1 = \frac{2eQ_{\perp}}{3kj_{\perp}} \ell n \left(\frac{n_0}{n_1}\right) \tag{6}$$

The value of heat flow $Q_{\perp}$ may be derived from the energy balance equation in the extraction volume. $Q_{\perp}$ represents the dominant heat input, since the flux of energetic primary electrons across the filter is small[2]. The energy loss in this volume is mainly due to convection by plasma electrons. Since there is a particle balance as well, the flux of electrons out equals the incoming flux, $Aj_{\perp}/e$, where A is the filter area. Hence the outgoing heat flux can be expressed as $A\alpha\, kT_1\, j_{\perp}/e$, where α is a constant which can be determined from the experimental data. The heat loss convected by ions is very small and is partially compensated by the input heat flux carried by the few primary electrons. Radiation losses can be neglected because of the very low electron temperature. Hence, if we can equate the input power to the outgoing power, we obtain

$$A\, Q_\perp = A\, j_\perp\, \alpha\, kT_1/e \qquad (7)$$

Substitution of Equation 7 in Equation 6 yields:

$$\frac{T_0 - T_1}{T_1} = \frac{2\alpha}{3} \ln\left(\frac{n_0}{n_1}\right) \qquad (8)$$

4. Discussion

Equation 8 can be tested by plotting the value of n_0/n_1, derived from Figs. 4 and 6, against the corresponding values of $(T_0 - T_1)/T_1$, derived from Figs. 3 and 5. This is shown in Fig. 7, where a single straight line is obtained for data obtained with varying both magnetic flux and arc current. Measurements by Pincosy[3] are also shown, which are also in agreement with Equation 8.

The slope in Fig. 7 gives a value of α of 2.5. This result is in good agreement with the theoretical value of $2kT_1$ for the energy removed per escaping plasma electron derived by Emmert et al[4] and Harbour[5].

The electromagnetic filter allows direct control of the electron temperature in the vicinity of the extraction system by inducing a density change across the filter. This can be of great importance in the design of negative ion sources, particularly for H^-, as Bacal[6] has shown that the production rate by dissociative attachment has a maximum at about an electron temperature of 1 eV. In addition the flux of electrons towards the extraction aperture is attenuated by the filter, thus reducing the extracted electron beam current.

Acknowledgement

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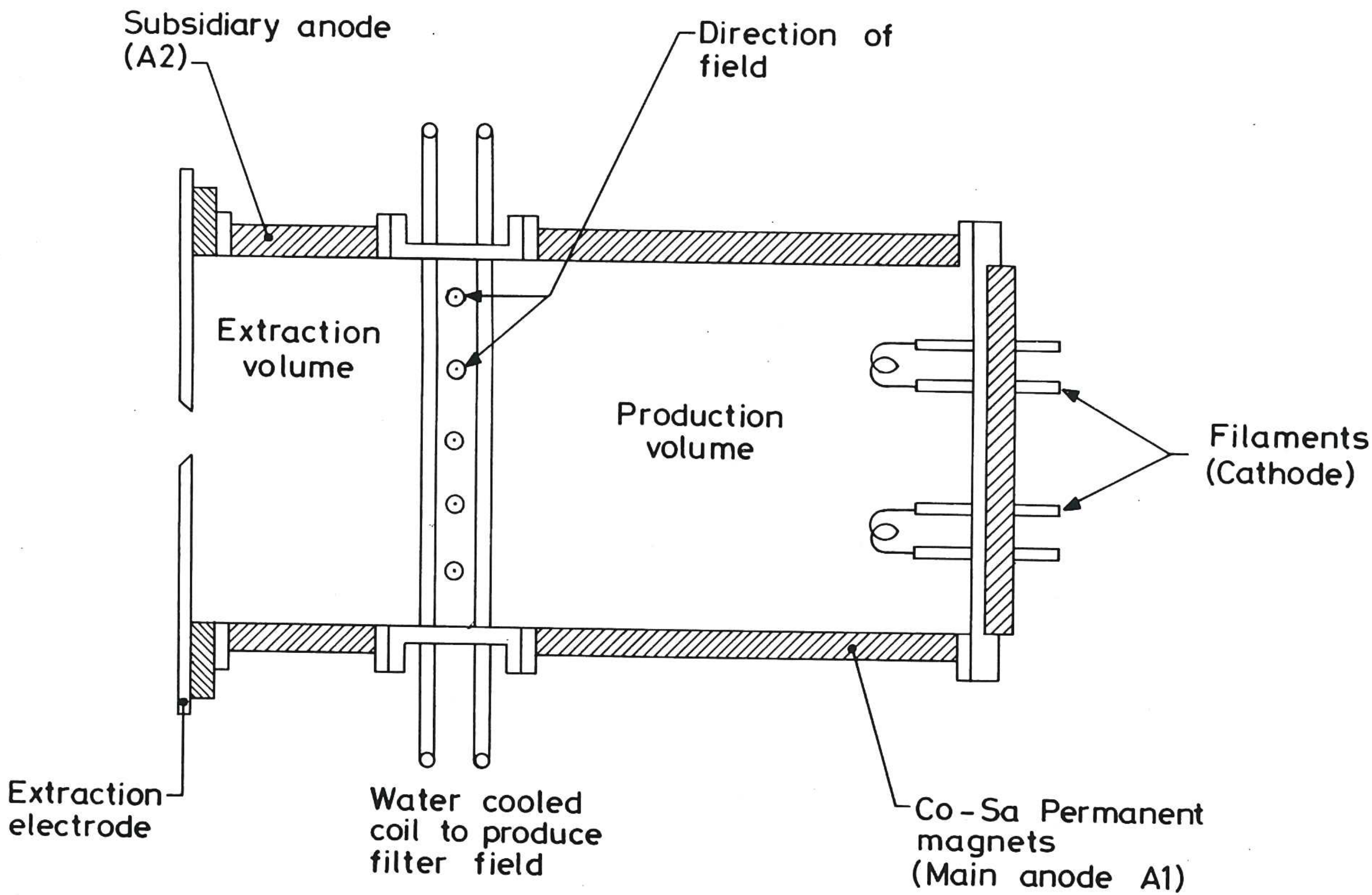

Fig.1 Cross-section view of the plasma source. The ion extraction electrode is on the left of the diagram.

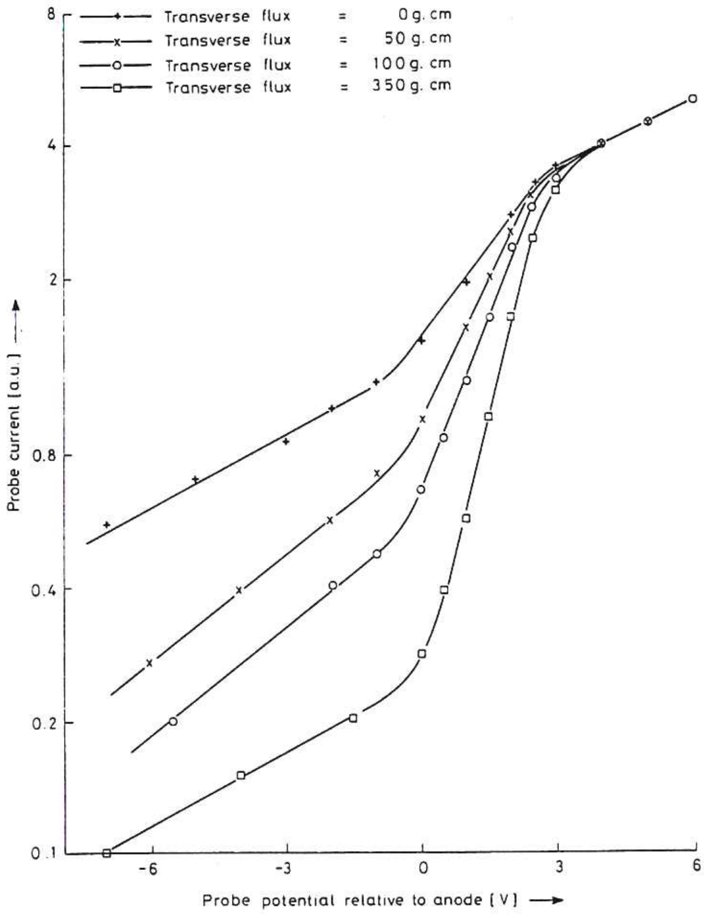

Fig.2 Langmuir probe characteristics in the extraction volume.

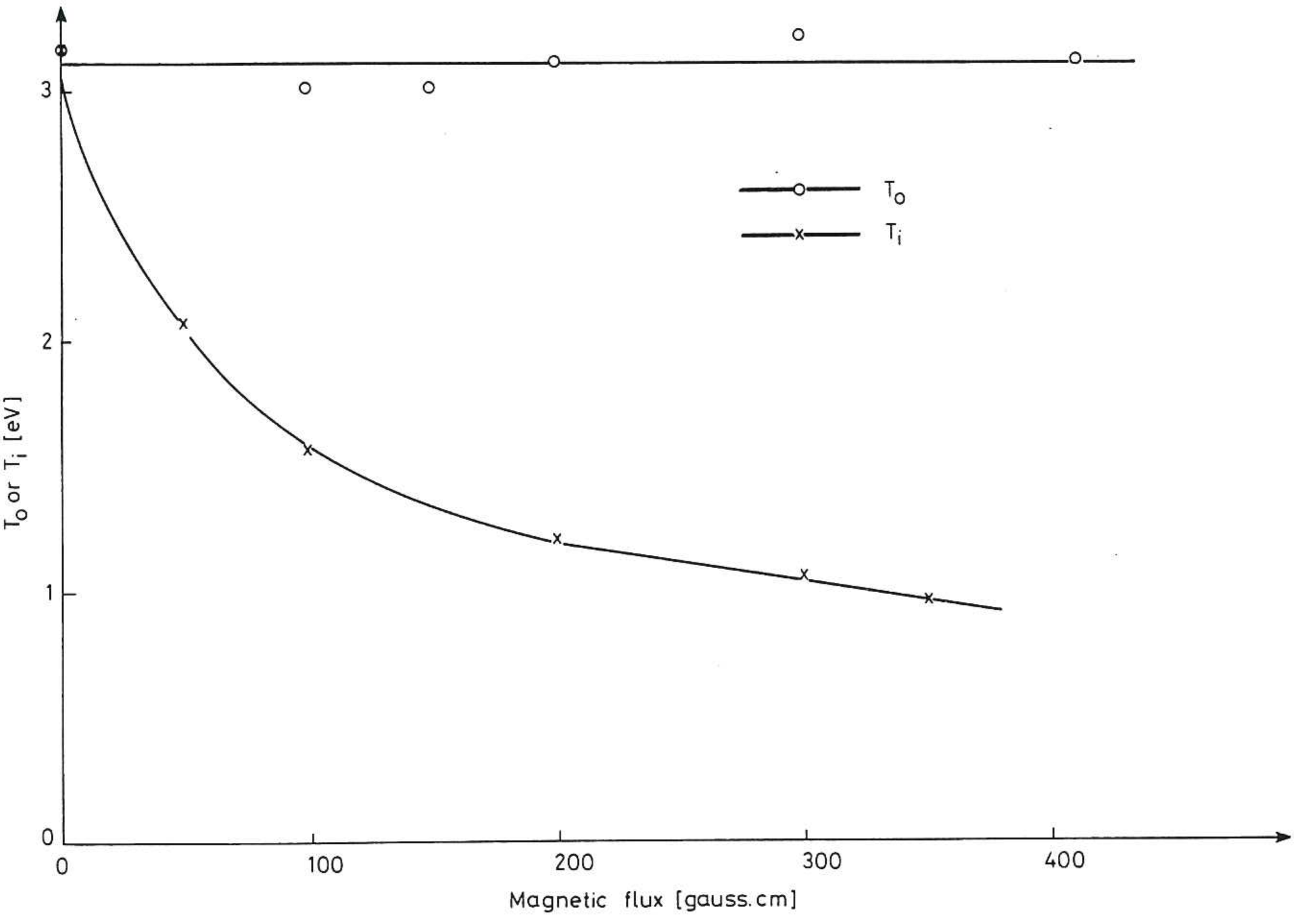

Fig.3 Dependence of the electron temperatures on the magnetic flux.

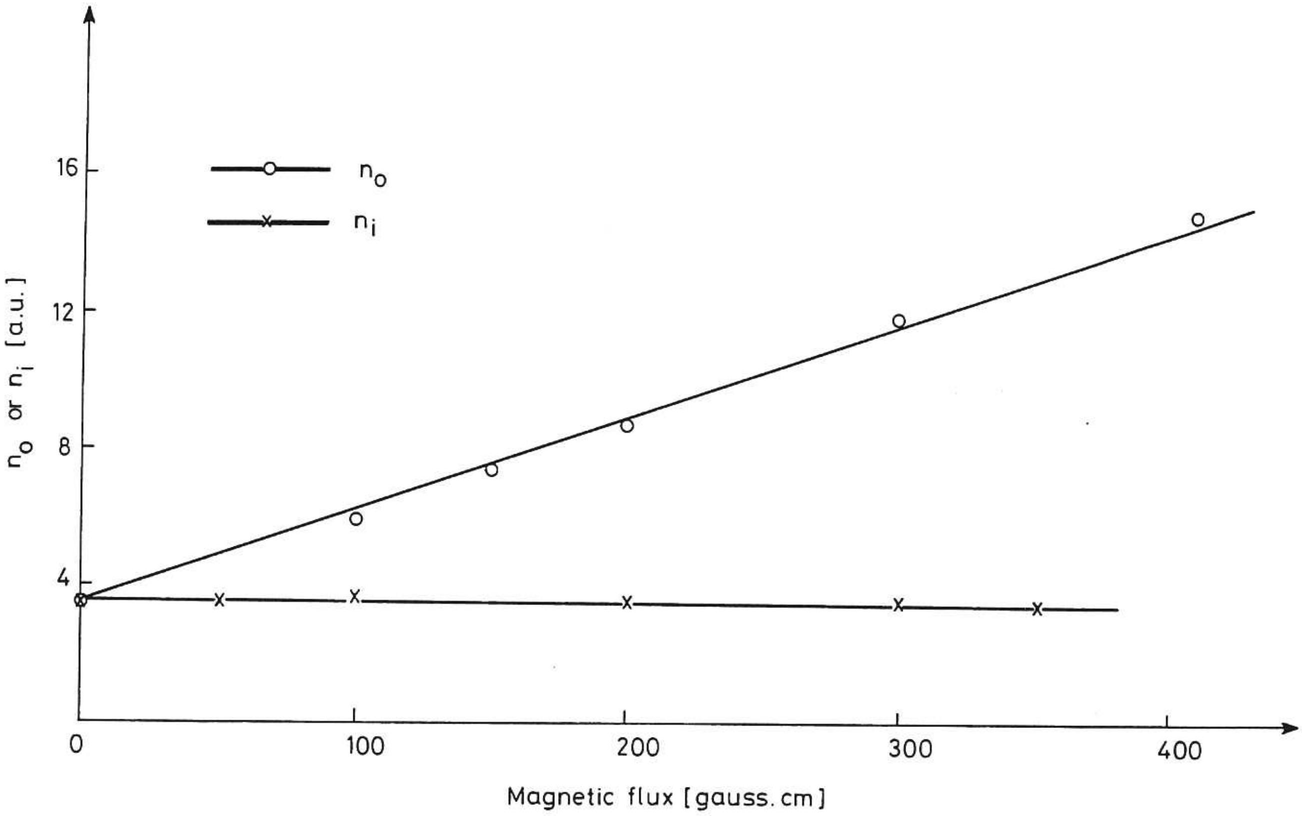

Fig.4 Dependence of the plasma densities on the magnetic flux.

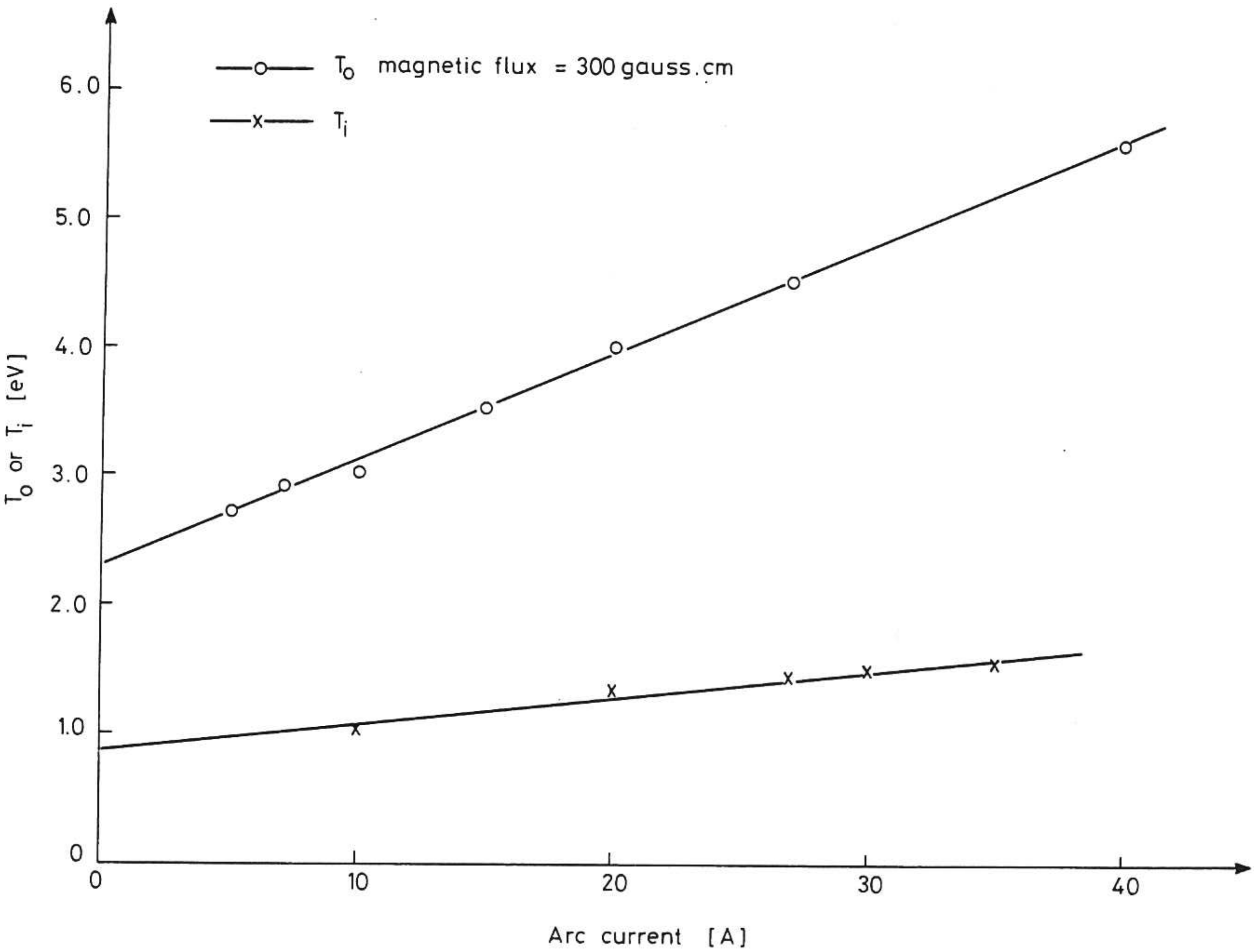

Fig.5 Dependence of the electron temperatures on the arc current.

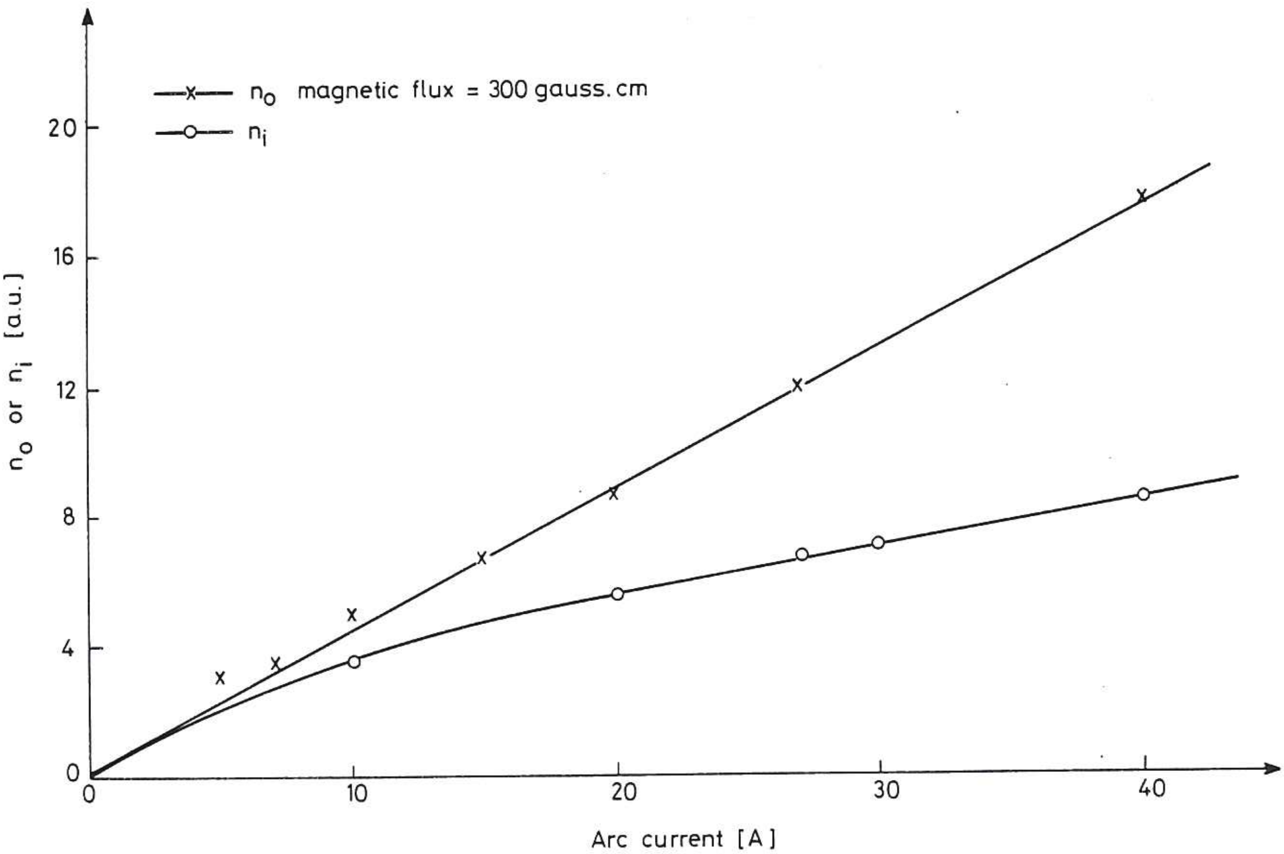

Fig.6 Dependence of the plasma densities on the arc current.

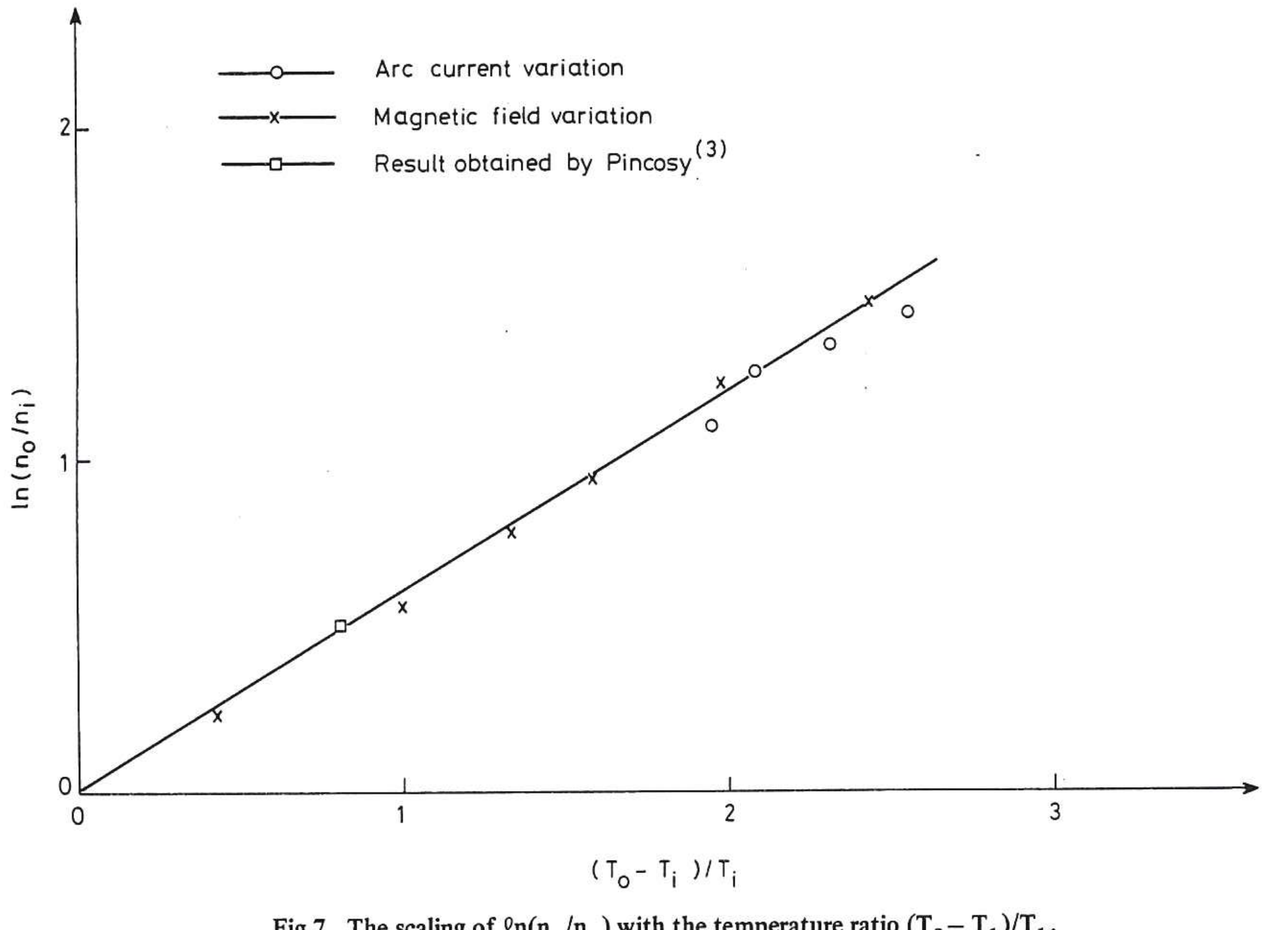

Fig.7 The scaling of $\ell n(n_0/n_1)$ with the temperature ratio $(T_0 - T_1)/T_1$. The result of Pincosy is shown by the square point.