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Part I. ION CONTAINMENT

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Part I. ION CONTAINMENT

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ABSTRACT

Optimisation of the operation of a P.I.G. discharge ion source for the production of multi-charged ions requires the use of a high power input into the discharge plasma, and good containment of the ions. Experimental data on the operating conditions of a P.I.G. source are analysed in terms of power and particle flux balance using the model of the source presented by Basile and Lagrange(2) in order to determine the power input to the plasma. From an extension of the analysis it is possible to estimate the ratio of the radial ion loss rate to the axial ion loss rate. A study of the variation of this ratio with magnetic field indicates those mechanisms which are responsible for the loss of ions from the source.

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1. INTRODUCTION

High current P.I.G. discharges have been used extensively for the production of multi-charged ions(1). Although Fuchs(2) has shown that it is necessary to operate the sources with high electron temperature and adequate ion containment times, there has been only a little discussion of how these parameters may be maximised(3).

The arc discharge characteristics have been discussed in a review article by Bennett(1) who shows that a feature of the normal mode of operation is that the cathodes are heated to thermionic emission temperature by bombardment by ions from the plasma. The importance of this factor to the balance of power in the discharge has been discussed by Basile and Lagrange(4,5,6), who derived relationships between the rate of ion production in the discharge, the ion component of the arc current, the electron component of the arc current and the arc voltage. Using these relationships Basile and Lagrange analysed their data, and derived estimates of the power used to heat the cathodes, and of the energy required to produce each ion in a discharge in nitrogen gas.

In the present investigation this analysis has been applied to evaluation of experimental data obtained with a P.I.G. discharge ion source developed for the Heavy Ion Axial Injector for the Harwell Variable Energy Cyclotron(7,8). The experimental arrangement of this source is described in Section 2. The analysis has been extended to the determination of the ratio of the ion current flowing to the cathodes to that flowing to the anode as discussed in Sections 3 and 4. This ratio equals the ratio of the time constant for radial loss τ_R to the time constant for axial loss τ_A. Data on the variation of τ_R/τ_A with magnetic field and the diameter of the discharge indicate which mechanisms determine these time constants and lead to an evaluation of the containment time of ions in the discharge.

2. EXPERIMENTAL ARRANGEMENT AND OBSERVATIONS

The P.I.G. discharge source used in these investigations is shown schematically in figure 1. It is mounted between the poles of a magnet, being introduced through holes in the pole pieces. Mild steel components are used in the source construction to reduce the perturbation of the magnetic field due to these holes(8). Most of the experiments were performed with an anode of 1 cm internal diameter and a cathode separation of 10 cm; the cathodes were made of 1.25 cm diameter tungsten rods 1.4 cm long and mounted on molybdenum stems. Tantalum cathodes were also used, and the anode and cathode diameters were changed in some experiments.

Ions are extracted from the source through a slit in the anode: the slit length is 16 mm and its width normally 1.5 mm. The total current of ions extracted is determined from the drain current from the source voltage supply. A systematic error may arise in this measurement due to the lack of complete suppression of secondary electrons.

Gas feed to the source is through two holes in the anode body, the gas passing from a high pressure reservoir to the source through a fixed high impedance. The flow rate is varied by varying the high pressure and is measured using a calibrated Hastings flow meter. Flow rates used are in the range 0 to 2 atm ccs/min. The arc power supply is connected between anode and cathode via 300 ohm resistance; and the arc current is maintained constant manually, there being no feed-back stabilisation.

In normal operation of the source as part of the injector system, the extracted ions are accelerated through a potential difference of about 20 kilovolts. They are then analysed as they pass through the magnetic field, the species required being transmitted through a slit at the focal plane of the magnetic selector(8). The range of magnetic field strength available in the present magnet is 0 - 5.5 kilogauss.

Figure 2 shows data on the variation of the arc characteristics and performance with gas flow rate for a constant arc current and constant magnetic field in nitrogen gas. A significant feature is that there is an optimum flow rate for production of the multi-charged ions. In a small range of flow rates above this optimum both the extracted ion current I_{ex} and the arc voltage V_A are almost constant at values which characterise the optimum flow rate. In the following sections consideration is given to the variation of the mean value of I_{ex} and V_A in this range of gas flow rates, with arc current and magnetic field strength.

3. MODEL OF POWER BALANCE

In discussing the power balance in the P.I.G. discharge it is necessary to introduce the following parameters:-

I_+	is total ion current being the product of the ion charge and the rate of production of ions, (the ion charge will be taken to be a single electron charge e)
βI_+	is the ion current to the cathode
$(1-\beta)I_+$	is the ion current to the anode
I_e	is the electron current in the arc
I_A	is the total arc current
V_A	is the arc voltage, it being assumed that the whole of the voltage appears across the cathode sheath
A_s	is the area of the extraction slit
A_A	is the surface area of the anode cylinder
ψ	is the energy expended in the plasma for each nitrogen ion produced
P_c	is the power required to heat the cathode to emission temperature
I_{ex}	is the extracted ion current

It then follows by definition that

$$I_A = I_e + \beta I_+ \tag{1}$$

$$I_{ex} = (1-\beta) I_+ \frac{A_s}{A_A} \quad . \tag{2}$$

The energy input to the plasma is $V_A I_e$, provided that the slowing down time of electrons is much shorter than the time of diffusion across the magnetic field. In a turbulent plasma, such as exists in this discharge, it is difficult to evaluate either of these times, both of which depend on the scattering time$^{(9)}$. However, in a strong magnetic field it seems likely that the diffusion time is the longer. We therefore equate $V_A I_e$ to the power required to produce the ions, viz:-

$$V_A I_e = \psi I_+ \quad . \tag{3}$$

The ions which bombard the cathodes carry a power $V_A \beta I_+$ to them; hence

$$P_c = V_A \beta I_+ \quad . \tag{4}$$

Eliminating I_e and I_+ one derives

$$V_A I_A = P_c + I_+ \psi = P_c + \frac{I_{ex}}{1-\beta} \frac{A_A}{A_s} \psi \tag{5}$$

and

$$\frac{\beta}{1-\beta} = \frac{P_c}{V_A I_{ex}} \frac{A_s}{A_A} \quad . \tag{6}$$

4. COMPARISON OF DATA WITH THEORY

Equation 5 relates the arc power to the extracted ion current. A plot of the experimental values (figure 3) shows a linear relationship implying that P_c and $\psi(1-\beta)$ are constant. The observation that P_c appears to be constant is in agreement with the measurements made by Basile and Lagrange$^{(6)}$ who showed that for a given cathode cooling configuration the variation in P_c is less than ± 10% over a wide range of operating conditions, in accordance with theoretical analysis of radiation cooling and thermionic emission characteristics. These authors show, in Reference 4, that ψ is also a slowly varying parameter. Finally as will be seen later β is small so that $1-\beta$ is close to unity and only slowly varying.

One can take the value of P_c to be the intercept on the ordinate in figure 3 and insert it in equation 6 in order to derive values of $\beta/1-\beta$. Using the values of β so obtained one can then re-estimate the value of P_c by plotting $V_A I_A$ against $I_{ex}/(1-\beta)$(Equation 5). By further re-iteration more accurate estimates of P_c and β can be made, and one can plot I_+ versus $V_A I_A$ and so derive a value for ψ. (figure 4). For the data presented in figure 4 the value of P_c obtained was 1050 ± 50 watts and was the same at each value of magnetic field. This value refers to new tungsten cathodes of 1.25 cm diameter. Higher values have been obtained as cathodes have aged, but no systematic study of this effect has been made. Tantalum cathodes have lower values of P_c than tungsten cathodes of the same dimensions.

The values of ψ and $\beta/1-\beta$ obtained can be in error due to systematic errors which may be as follows:

(1) There may be errors in the determination of the extracted ion current due to insufficient suppression of secondary electrons.

(2) The mean charge state in the extracted current may not be the same as that in the current flowing to the anode. If they are equal to each other but are not unity then the value of ψ derived will be the energy expended per ion produced divided by the mean charge on the ions.

(3) The current flowing to the anode may not be distributed uniformly along the length of the anode, so that the ratio of $(1-\beta)I_+$ to I_{ex}

may not be equal to A_A/A_S.

A particular type of non-uniformity is that in which the currents flowing through the two cathodes differ from each other. Such a situation has occurred in some of the experiments and can arise when one of the gas inlets becomes covered by sputtered cathode material. When this happens the extracted current is found to decrease in value and high values of β are obtained. It must be noted that rarely are the cathode currents equal, so that there may always be some error from this source.

In principle it is possible to design an experiment in which the sources of error in (1) and (3) can be eliminated. However, this could not be done in the present installation of the ion source in the axial injector system. As a result the absolute values obtained for ψ and $\beta/1-\beta$ must be treated with caution.

The values of ψ derived from the data in figure 4 varied with magnetic field strength being 90 eV at 1.2 kilogauss, 110 e.v at 2.45 kilogauss and 160 eV at 3.7 kilogauss. These compare with values quoted by Basile and Lagrange(4) which lie in the range 65 to 130 eV.

Using this analysis of the data values of $\beta/1-\beta$ have been derived at various magnetic field strengths. Results are shown in figure 5a for a discharge in nitrogen at 8 amps arc current. The variation of $\beta/1-\beta$ with arc current is shown in figure 5b for a magnetic field strength of 2.45 kilogauss. Data for argon discharges are presented in figures 6a and 6b

Measurements have also been made in sources of different diameters. Some results are shown in figure 7.

5. DISCUSSION OF ION CONTAINMENT MEASUREMENTS

The quantity $\beta/1-\beta$ can be related to the ratio of the time constant for radial loss of ions, τ_R, to the time constant for axial loss of ions τ_A. If the radial velocity of an ion at any point is a function of the radius only and if the axial velocity at any point is a function of the axial displacement only, then

$$\frac{\beta}{1-\beta} = \frac{\tau_R}{\tau_A}$$

where τ_R can be identified as the average time taken for an ion to escape radially and τ_A the average time taken for an ion to escape axially.

More generally the velocities are functions of both radius and axial position but one may write this identity provided that one defines τ_R and τ_A as the effective loss times for radial and axial motion.

5.1 Data in 1 cm Diameter Source

The data in figure 5a show that τ_R/τ_A varies with magnetic field, approaching a line

$$\tau_R/\tau_A = 0.11 \text{ B} \times 10^{-3}$$

at high field strengths, and approaching a constant value of about 0.2 at low field strengths. Data obtained at other arc currents in the range 3 to 10 amps also show that τ_R/τ_A approaches a limit of 0.2 at low field strengths.

One may infer that at the higher field strengths τ_A is constant whilst τ_R increases linearly with B as would occur if the radial loss were due to Bohm diffusion$^{(10)}$. The experimental data taken over a range of arc currents in both nitrogen and argon show that the slope of the linear section of the curve of τ_R/τ_A versus B varies with arc current, and with the gas. Further investigations are required to elucidate the relationships between the slope and these parameters.

At low field strengths τ_R cannot decrease to zero but must approach a time equal to the transit time of ions accelerated by the radial electric field. In this limit the "free fall" model of ion containment discussed by Tonks and Langmuir$^{(11)}$ applies, and the value of τ_R will be approximately equal to $2\,R.\left(\frac{M_i}{2Z_i e\,\varphi_o}\right)^{\frac{1}{2}}$, where R is the radius, M_i the ion mass, Z_i e the ion charge and φ_o the potential difference from the centre of the discharge to the plasma boundary at the anode. If the axial motion is also due to an axial electric field of order $2\varphi_o/L$ and free-fall conditions apply, then τ_A will be approximately $L\left(\frac{M_i}{2\,Ze\,\varphi_o}\right)^{\frac{1}{2}}$ where L is the length of the discharge chamber.

One would expect therefore that

$$\frac{\tau_R}{\tau_A} \simeq \frac{2R}{L} .$$

R being the discharge radius (0.5 cm) and L the discharge length. Taking L to be the separation of the cathode i.e. 10 cm one obtains a value of 0.1; if L is the length of the narrow section of the discharge (the so called chimney) i.e. 6 cm, the ratio is 0.167. These values compare with the experimental estimate for the lower limit of $\frac{\tau_R}{\tau_A}$ of < 0.2 in both nitrogen and argon (figures 5a and 6a).

The agreement is sufficiently good as to indicate that this interpretation is reasonable, i.e. that at low magnetic fields the radial and axial motions are "free fall" in the gradients of the plasma potential.

In order to make a more precise comparison and to derive absolute estimates of τ_R and τ_A separately it is necessary to know the potential φ_o and how it varies both radially and axially. Two calculations of the axial potential gradient have been discussed in the literature, varying in their assumptions concerning the energy spectrum of the electrons in the discharge. Saltz et al(12) assume that the electrons emitted by the cathode, which are accelerated across the cathode sheath and trapped in the reflex discharge with only little energy loss, these being the so-called primary electrons, dominate. They do take account of the secondary electrons produced in ionisation, assuming that these electrons oscillate in the potential well without energy loss until scattered out. This calculation predicts a large potential change in the plasma of about 70 volts. Experiments, reported by these authors, using low currents (< 1 amp) in a P.I.G. discharge, exhibit a potential variation close to that calculated.

In the opposite limit in which the secondary electrons thermalise rapidly and dominate over the primary electrons, it has been shown by Harrison and Thompson(13) that the maximum potential variation within the plasma is of the order of $\frac{k\,T_e}{e}$ expressed in volts. There is no experimental confirmation of this model, but one might expect that at the high arc currents used in this investigation the turbulence in the plasma would lead to rapid thermalisation, so that this model would be more applicable.

Furthermore, if the model proposed by Salz et al were valid for this situation then one would not expect the power balance analysis represented by equations 3 and 4 to be applicable, because the primary electrons do not deposit much energy in the plasma in this model, and because the escaping ions take energy from the plasma in the form of potential energy. In view of the agreement between the experimental data and equation 5, which derives from equations 3 and 4, it seems unlikely that the model due to Salz et al is applicable in this experiment.

Taking the model due to Thomson and Harrison to be valid, Green(3) has calculated the axial containment time to be $0.7\ LT_e^{-\frac{1}{2}}(\frac{Z}{A})^{-\frac{1}{2}} \times 10^{-5}$ secs, one can similarly estimate the radial containment time to be $1.4\ RT_e^{-\frac{1}{2}}(\frac{Z}{A})^{-\frac{1}{2}} \times 10^{-5}$ secs for T_e in electron volts.

It should be noted that this interpretation of ion motion in terms of free-fall in axial and radial potential gradients is at variance with the observations of an axial potential well reported by Makov(14) in a pulsed high current P.I.G. discharge used for the production of multi-charged ions. Makov(14) postulated that the formation of the well was due to the high level of plasma density near the cathodes produced by ionisation of the tungsten atoms sputtered from the cathodes. A possible explanation of the difference between the two observations may be that in the pulsed system the heavy tungsten atoms do not have time to migrate far, whilst in the D.C. source used in these studies they can migrate further.

5.2 Data in Larger Diameter Sources

Measurements were also made in sources of 1.5 cm and 2 cm internal diameter with the same 10 cm cathode spacing as above, but with tantalum cathodes. It was found that the arc voltage and extracted current varied more with gas flow than previously and it was difficult to determine the optimum flow rate. Consequently, data were obtained at a number of flow rates for a range of arc currents and magnetic field values.

The data shown in figures 7a and b indicate higher values of τ_R/τ_A as one would expect in discharges of larger diameter. However, the values of τ_R/τ_A do not increase continuously with magnetic field strength but reach a maximum value and then decrease. A possible explanation of this effect is the onset of a loss rate which increases linearly with B, for example one in which the ions have radial velocities of order $B/(8\pi\rho)^{\frac{1}{2}}$ where ρ is the density of the plasma. Such a velocity can arise if the plasma is magnetohydrodynamically unstable. In order to test this possibility, the data has been compared with a simple calculation of the loss rate, in which it is assumed that:-

(i) τ_A is constant

and (ii) τ_R is given by the equation

$$\frac{1}{\tau_R} = \frac{\alpha_1}{B} + \alpha_2 B \quad . \tag{7}$$

($\frac{\alpha_1}{B}$ derives from the Bohm diffusion term and $\alpha_2 B$ from the proposed magnetohydrodynamic loss).

Hence

$$\frac{B\tau_A}{\tau_R} = \alpha_1 + \alpha_2 B^2 \quad . \tag{8}$$

Values of $\frac{B\tau_A}{\tau_R}$ are shown as a function of B^2 in both nitrogen and argon discharges in figure 8. Whilst the data for nitrogen follow this relationship of equation (8) well over the range of magnetic field strengths used, the data for argon show a break. This suggests that there is a threshold magnetic field strength for the onset of the magnetohydrodynamic motion.

The threshold field strengths in argon are found to vary with the gas inflow and agree closely with the values reported by Nezlin$^{(15)}$ for the onset of instabilities in P.I.G. discharges (fig.9). Nezlin shows that at low flow rates the variation of the threshold field strength is consistent with the relation

$$\frac{eB}{Mc} \times \frac{1}{n_o \sigma_o v_i} \sim 1$$

where M is the ion mass, n_o the neutral density, σ_o the ion-neutral elastic scattering collision cross-section and v_i the ion velocity, and thus suggests that the instability is the drift dissipative instability (Kadomtsev$^{(16)}$).

It should be noted that this expression would predict the threshold in nitrogen to be less than 0.2 times that in argon, depending on the elastic scattering cross-section and ion energy. This is consistent with the fact that no threshold has been observed in nitrogen over the range of field strengths used which extend from 1 kilogauss upwards.

6. CONCLUSION

From analysis of the balance of power in a P.I.G. discharge, and the arc characteristics and source performance it was possible to derive values for the ratio of τ_R/τ_A, i.e. of the ratio of the effective radial loss time to the effective axial loss time. Although absolute values obtained must be treated with caution, it seems possible to identify some of the loss mechanisms involved.

(a) Axial loss by free fall in a potential gradient

$$\tau_A \simeq 0.7 \;.\; \times L.\; T_e^{-\frac{1}{2}} \left(\frac{A}{Z} \right)^{\frac{1}{2}} .\; \times 10^{-6} \text{ secs}$$

(b) Radial loss by free fall in a potential gradient which occurs at low magnetic fields such that

$$\frac{(M\ k\ T_e)^{\frac{1}{2}} c}{eB} > R$$

$$\tau_R \simeq 1.4 . x R. T_e^{-\frac{1}{2}} \left(\frac{A}{Z} \right)^{\frac{1}{2}} x\ 10^{-6} \text{ secs.}$$

(c) Radial loss by Bohm diffusion

$$\tau_R = C_1 \quad B.R^2/T$$

(d) Radial loss due to a magnetohydrodynamic instability

$$\tau_R = C_2 \quad \frac{R\rho^{\frac{1}{2}}}{B}$$

Further investigations are required to elucidate how the constants C_1 and C_2 depend on the plasma parameters.

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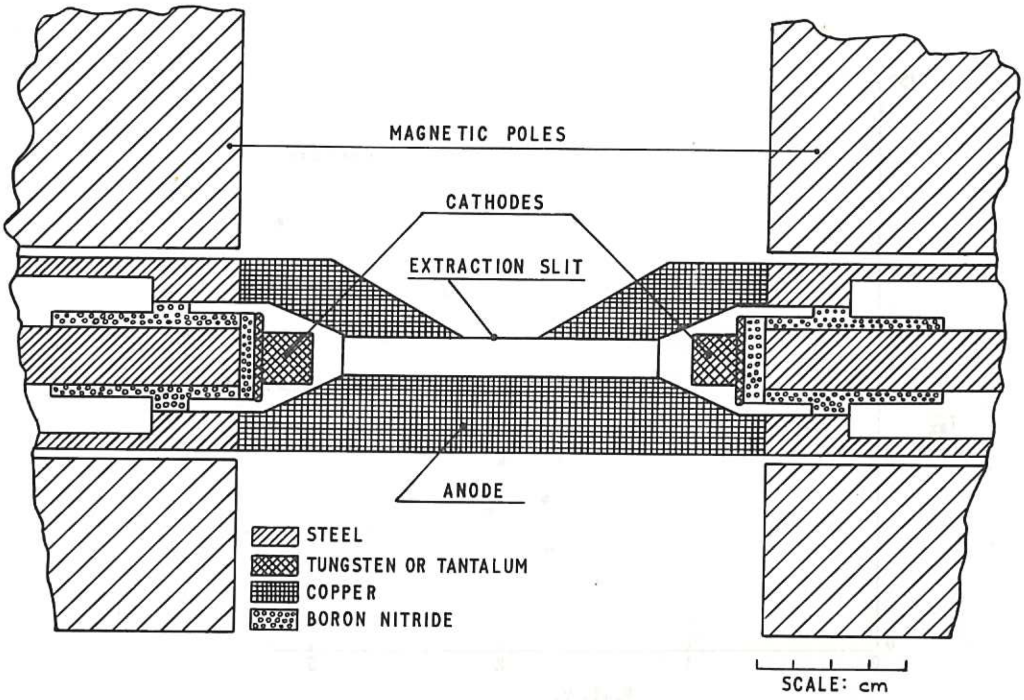

Fig.1 Schematic of P.I.G. Discharge Ion Source.

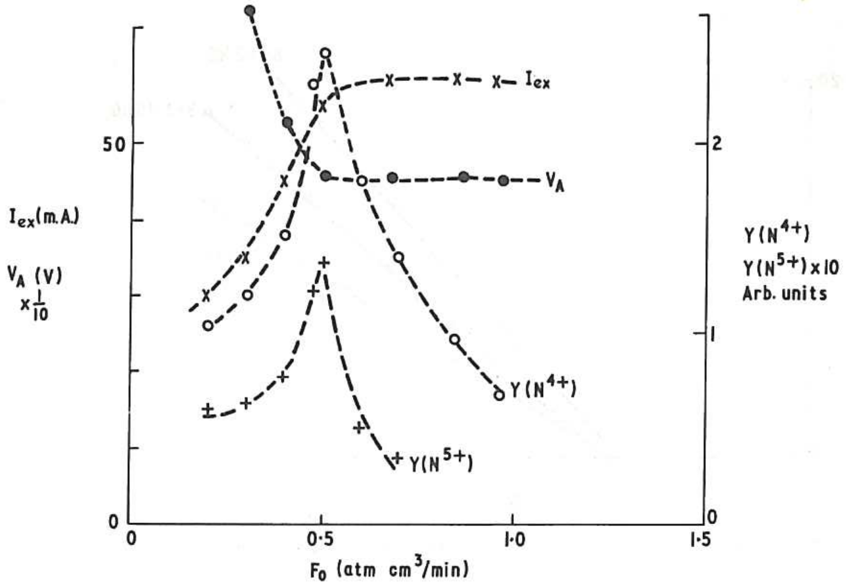

Fig.2 Variation of Discharge Parameters with Gas Flow Rate F_0. (I_{ex} is extracted ion current, V_A arc voltage, Y(N^{4+}) and Y(N^{5+}) the current of N^{4+} and N^{5+} ions.)

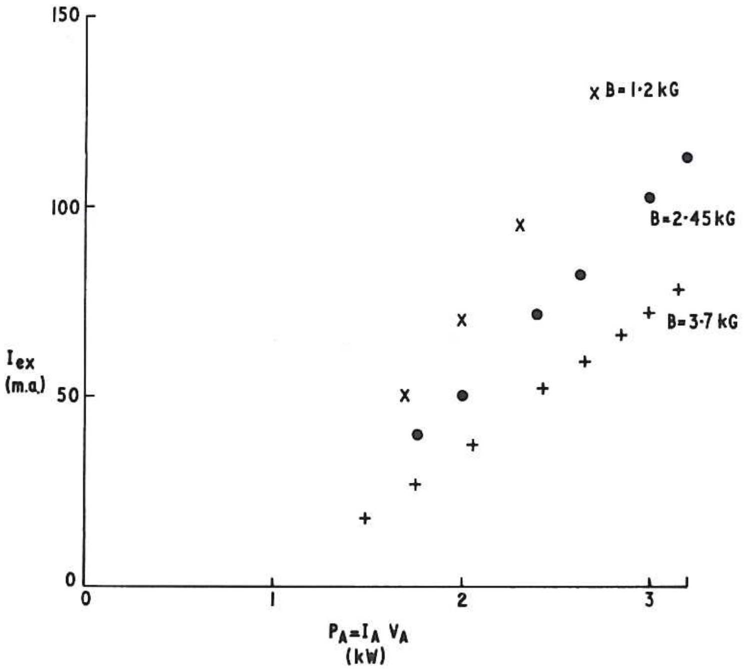

Fig.3 Variation of Extracted Ion Current I_{ex} with Arc Power P_A. (Argon gas in 1 cm diameter discharge and tungsten cathodes.)

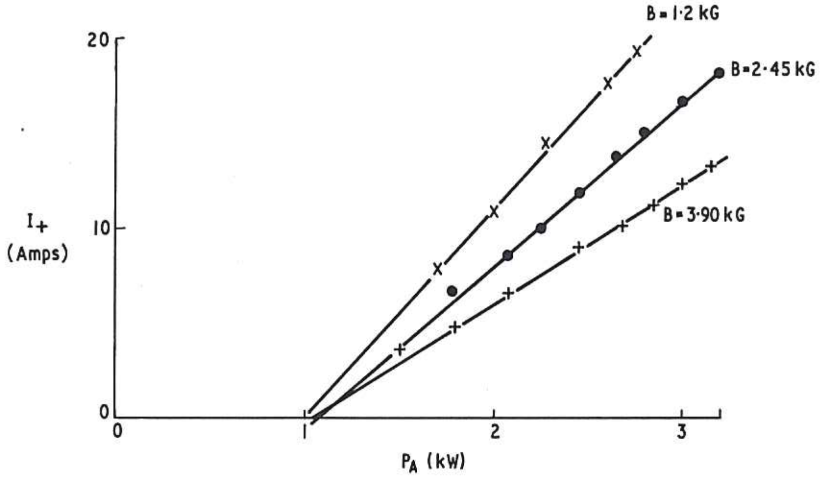

Fig.4 Variation of Total Ion Current I_+ with Arc Power derived from Fig.3

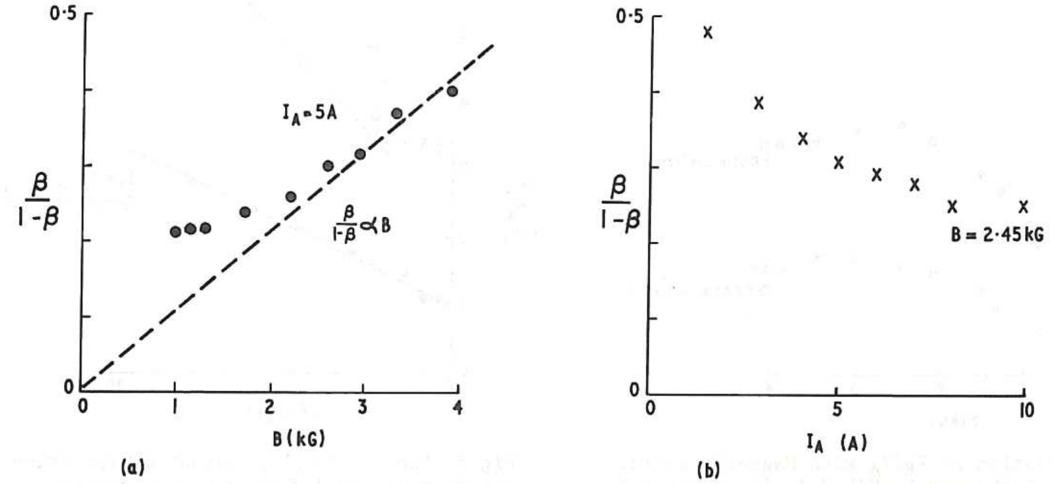

Fig.5 (a) Variation of $\beta/1-\beta$ with Magnetic Field.
(b) Variation of $\beta/1-\beta$ with Arc Current.
(Nitrogen gas 1 cm diameter discharge tungsten cathodes.) (Note that $\beta/1-\beta$ equals τ_R/τ_A.)

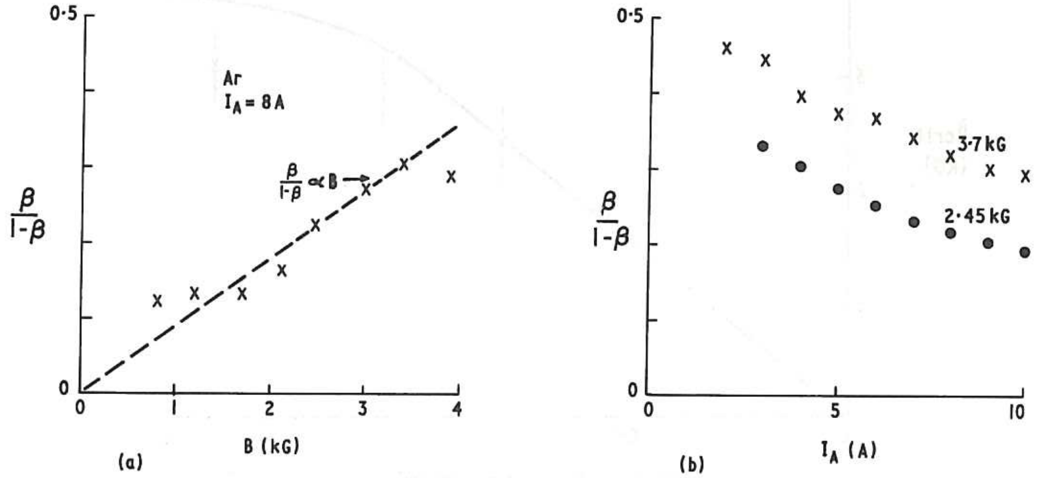

Fig.6 (a) Variation of $\beta/1-\beta$ with Magnetic Field.
(b) Variation of $\beta/1-\beta$ with Arc Current.
(Argon gas 1 cm diameter discharge tungsten cathodes.) (Note that $\beta/1-\beta$ equals τ_R/τ_A.)

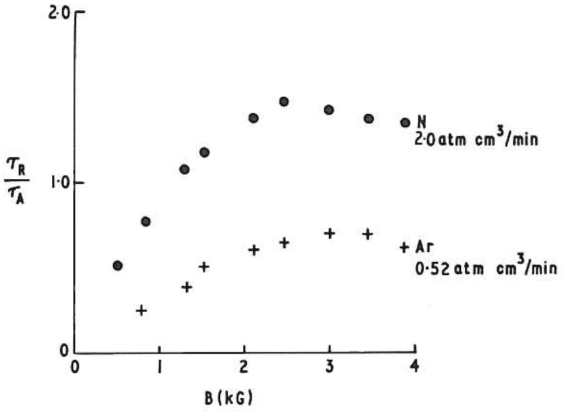

Fig.7 Variation of τ_R/τ_A with Magnetic Field. (Note that τ_R/τ_A equals $\beta/1-\beta$.) (Nitrogen and Argon Gas 1.5 cm diameter discharge - tantalum cathodes.)

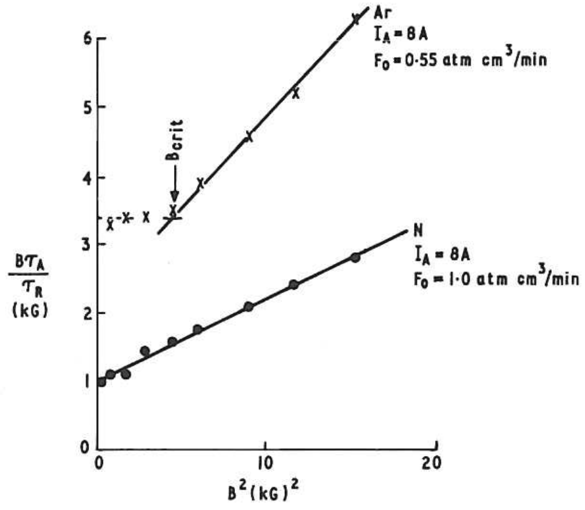

Fig.8 Plot of $B\,\tau_R/\tau_A$ against B^2 for Argon and Nitrogen in 1.5 cm diameter source.

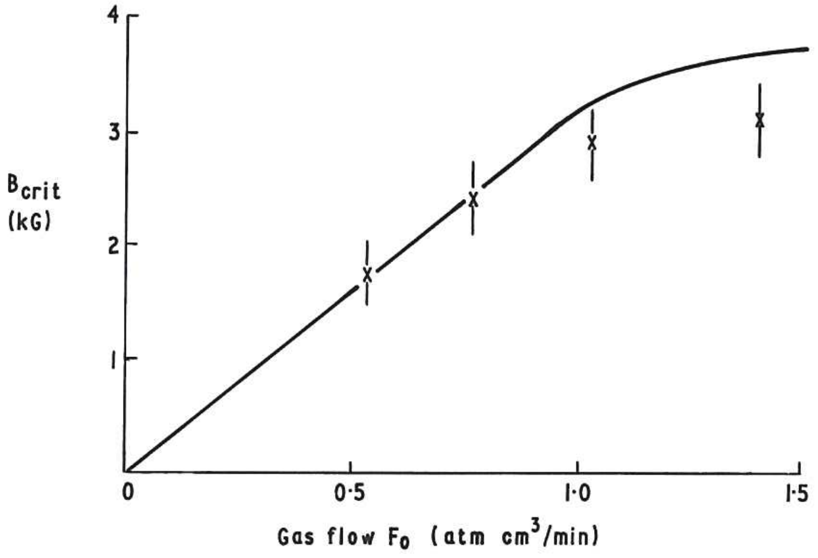

Fig.9 Variation of Threshold for Magnetohydrodynamic Loss Process with Gas Flow Rate in Argon. (Experimental points with estimated errors ✱ Solid line from Nezlin(14).)