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POWER AND PARTICLE FLUX BALANCE IN A P.I.G. DISCHARGE ION SOURCE

Part 2. IONISATION

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Part 2. IONISATION

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ABSTRACT

The ion current which can be extracted from an ion source depends on the degree of ionisation of the neutral gas which can be attained. An analysis is presented of the ionisation in a P.I.G. discharge ion source, in which it is assumed that ionisation is due dominantly to the impact of thermal electrons with neutral atoms. Implications of this analysis for the operating conditions of the source are discussed and comparison is made with experimental data.

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1. INTRODUCTION

Several authors have reported the experimental observation that the yield of multi-charged ions from P.I.G. discharge ion sources rises at low gas input flow rates (see Bennett$^{(1)}$ for references and a survey of data). In figure 2 of Part I of this report$^{(2)}$, data were presented which showed that the yield of multi-charged ions peaked at a low flow rate, and that the arc characteristics showed changes at this flow rate. In an attempt to explain these observations, consideration has been given to the problem of particle flux balance in the discharge. This problem has been examined earlier by Chavet-Choueka$^{(3)}$, on the assumption that neutral atoms are ionised by impact with energetic or primary electrons from the cathodes. However, as pointed out by Fuchs$^{(4)}$, ionisation is more probably due to impact with thermal plasma electrons at the densities and temperatures obtained in these ion sources.

In this paper a model of particle flux balance is proposed in which it is assumed that ionisation is due solely to the thermal electrons (Section 2). The predictions of the model are compared with experimental data in Section 3.

2. PARTICLE FLUX BALANCE

2.1 Derivation of Basic Equations

The parameters of the discharge to be used in this discussion are those listed in Part I of this report, with the addition of F the input gas flow rate in atoms per sec, and J_o the outward flux density of neutral atoms at the walls of the arc chamber assumed to be uniform throughout the chamber.

The first condition to be considered for particle flux balance is that

F must be balanced by the efflux of ions and neutrals from the extractor slit and the absorption of ions and neutrals on the walls of the arc chamber

$$eF = eJ_o A_s + (1-\beta) I_+ \frac{A_s}{A_A} + \gamma J_o (A_A - A_s)\, e$$

$$+ \gamma (1-\beta) I_+ (1 - \frac{A_s}{A_A}) \quad . \qquad (1)$$

The absorption arises in this case from the pumping effect of sputtered cathode material deposited on the anodes, one does not have any contribution therefore from ions flowing to the cathode. It is assumed that the absorption co-efficient γ is the same for ions and neutrals.

A second condition arises from the balance of ion production rate against the rate of ionising neutrals.

$$I_+ = p \Big[eF + eJ_o (A_A - A_s)(1-\nu) + eJ_o A_c$$

$$+ \beta I_+ + (1-\beta) I_+ (1 - \frac{A_s}{A_A})(1 - \gamma) \Big] \qquad (2)$$

where A_c is the cathode area and is sufficiently small compared to A_A that it can be neglected, and p is the probability of ionisation of a neutral in traversing the discharge being given by

$$p = 1 - \exp(-n_e < \sigma v > \tau_o) \quad , \qquad (3)$$

In equation 3, n_e is the mean electron density in the discharge and τ_o the average time of flight of a neutral across the discharge chamber being of order of the diameter D divided by the neutral velocity v_o. The parameter $< \sigma v >$ is the rate co-efficient for ionisation of the neutrals by impact with thermal electrons being the average of the product of the ionisation cross-section(σ) and the electron velocity(v) taken over the thermal electron velocity distribution function(5).

However n_e can be related to I_+ since

$$\frac{n_e V_o e}{\tau} = I_+ \tag{4}$$

where V_o is the plasma volume and τ is the mean ion containment time. A basic assumption in writing equation 3 and 4 in these forms is that the shapes of the axial and radial distributions of plasma density in the discharge volume do not change appreciably as other parameters change. This means that $n_e < \sigma v > \tau_o$ should be small, i.e. the mean free path for ionisation should be long compared with the diameter of the discharge chamber.

By reducing equations 1 - 4 one derives the result

$$\frac{e\,F_o}{I_{+o}} = -\frac{e\,F_o}{I_+} \log \left[1 - \frac{1}{\dfrac{e\,F_o}{I_+} + \beta} \right] \tag{5}$$

where F_o equals $\dfrac{F}{\gamma + \dfrac{A_S}{A_A}}$ and I_{+o} equals $\dfrac{V_o e}{< \sigma v > \tau . \tau_o}$.

2.2 Variation of Ionisation Rate with Flow Rate

Equation 5 shows the relationship between the parameter I_{+o}, the gas flow rate and the total ion current: using the equation in the form presented above one can calculate the variation of $e\,F_o/I_{+o}$ with $\dfrac{e\,F_o}{I_+}$. Results obtained for the case β equal to zero are shown in figure 1. It is observed experimentally that I_+ is almost constant over a range of flow rates F above the lowest value at which the arc can be maintained (see section 3.1). It follows, therefore, from equation 5 that in this range of flow rate, the variation in F_o produces a variation in I_{+o}. Further, since V_o and τ_o are constants, it is $< \sigma v > \tau$ which must vary.

The rate coefficient $< \sigma v >$ is a function of the electron temperature, being given by the expression$^{(5)}$

$$< \sigma v > \simeq \frac{0.90 \times 10^{-5}}{\varphi^{3/2}} \cdot \frac{(T/\varphi)^{\frac{1}{2}}}{(4.88 + T/\varphi)} \exp\left(- \varphi/T\right)$$

where the electron temperature, T, and the ionisation potential φ are both expressed in electron volts. In addition τ may be a function of the electron temperature. Thus a variation of $< \sigma v > \tau$ implies a variation of the electron temperature. As the flow rate decreases, the plasma maintains a constant ion production rate because of the higher ionisation rate coefficient and thus temperature.

However, $< \sigma v > \tau$ may have a limiting upper value as can be seen from Figure 2 where this product is plotted as a function of temperature T for three cases:- (a) τ independent of T, (b) τ varying as $T^{-\frac{1}{2}}$ (c) τ varying as T^{-1}; corresponding to the three dominating ion loss mechanisms, discussed in Part I, namely:- hydromagnetic instability, free fall and Bohm diffusion. It follows that if $< \sigma v > \tau$ has an upper limit, then there is a lower limit to the flow rate below which ionisation can no longer maintain a constant total ion current. At this limit the electron temperature would rise to a value corresponding to that for which the product $< \sigma v > \tau$ has its maximum.

The value of this flow rate limit depends on the maximum value of $< \sigma v > \tau$, on the total ion current I_+ and on the parameters V_o, τ_o appearing in equation 6. In general the relationship is not simple; however one can make two approximations,

(a) at low values of I_+

$$F_o \simeq I_{+o}$$

i.e.

$$F_o \simeq (\gamma + \frac{A_s}{A_A}) \left[\frac{V_o e}{(< \sigma v > \tau)_{max} \cdot \tau_o} \right] \qquad (6)\ \cancel{(7)}$$

(b) at high values of I_+/I_{+o},

$$F_o \simeq (1 - \beta) I_+ ,$$

which corresponds to 100% gas utilisation; but, in this limit the model breaks down since then the mean free path for ionisation becomes less than the average transit distance of neutrals.

3. COMPARISON OF EXPERIMENT AND THEORY

3.1 Identification of Limiting Flow Rate

The data obtained in nitrogen discharges which indicated the existence of a lower limit to the flow rate for normal mode operation are shown in figure 3.

In general it is observed in nitrogen that the extracted ion current and arc voltage vary only slowly with decreasing flow rate down to a lower limit at which the arc voltage starts to rise rapidly - at constant arc current, and the extracted ion current starts to fall. The analysis presented in part I indicates that this condition corresponds to a change from a constant rate of ion production to a rapidly decreasing rate. It seems reasonable therefore to identify the flow rate at which this change takes place, F_c, as the lower limiting flow rate predicted by the model presented above.

It should be noted at this point that identification of the limiting flow rate is not always simple. It is possible for the presence of impurities and of atoms released from the cathode by sputtering to modify the arc characteristics and their dependence on flow rate. Instabilities of source operation can also make observations difficult.

3.2 Parametric Dependence of Limiting Flow Rate

The value of F_c is generally about 0.5 to 1.0 atm cc/min. If all the gas emerged as singly charged ions one would have currents of 75 to 150 mA, however since the mean charge state is close to two for nitrogen (Bennett[(1)]), full gas utilisation would give twice these currents. The observed currents are in the range of 20 to 80 mA, thus indicating only partial gas utilisation, i.e. $F_0 > (1-\beta)\ I_+$. In this case F_c approaches the value given in equation 6.

Measurements were made in nitrogen at 2.45 kilogauss magnetic field and with an arc current of 8 amps, for two extraction slit widths one of 1.0 mm and the other 1.5 mm. F_c was observed to change from 0.6 ± 0.1 atm ccs/min to 0.9 ± 0.1 atm ccs/min, which is consistent with equation 6 when γ, the probability of wall obsorption of particles, is less than 10^{-3}.

Using the 1.5 mm slit, measurements were made at different magnetic field strengths and arc currents. Since equation 6 relates F_c to τ, a plot has been made of the variation of $F_c \frac{\tau_R}{\tau_A}$ with $\frac{\tau_R}{\tau_A}$ (figure 4). Only a limited range of parameters was used due to the difficulties discussed above. The data do show that $F_c\ \tau_R/\tau_A$ increases as τ_R/τ_A increases implying from equation 6 that $< \sigma v >$ must decrease.

This observation is qualitativly in agreement with the predictions of this model, that the maximum value of $< \sigma v >$ obtained at F_c depends on how the ion containment time varies with temperature. As discussed above and in part I, at low values of τ_R/τ_A, both τ_R and τ_A scale as $T^{-\frac{1}{2}}$ and $< \sigma v > \tau$ maximises at T equal to 3φ. At higher values of τ_R/τ_A where Bohm diffusion dominates τ_R scales as T^{-1} and $< \sigma v > \tau$ maximises at T equal to 1.44φ. The parameter $< \sigma v > \tau$ decreases from one extreme to the other by 26%. The observed change in $F_c \frac{\tau_R}{\tau_A}$ corresponds to a larger decrease being at least 42%.

3.3 Yield of N^{4+} and N^{5+} Ions

As shown in figure 3, the yield of both N^{4+} and N^{5+} ions reaches a maximum at the flow rate identified as F_c. This observation is consistent with the prediction that $< \sigma v > \tau$ and hence the electron temperature reach their maximum value at this flow rate.

Measurements have also been made of the yields at different magnetic field strengths. The data are shown plotted as a function of τ_R/τ_A in figure 4. As shown by Fuchs(4) the yield of highly charged ions should increase with ion containment time τ if the electron temperature is constant. In this experiment $\tau \simeq \tau_R < \tau_A$, so one would expect an increase in the yield with increasing τ_R/τ_A. However, the data show a decrease, implying that the electron temperature decreases as τ_R/τ_A increases. This implication is consistent with the interpretation of the data on F_c presented in the section above.

4. CONCLUSION

The model of ionisation of the gas in a P.I.G. discharge presented in this paper shows that ionisation cross-section and thus electron temperature must adjust themselves to a value consistent with the required rate of ion production and gas input. This prediction is analogous to that made by Demikharnov et al(6) and Lejeune(7) in the case of ionisation by an electron beam in duoplasmatrons; the cross-section for ionisation by the beam depends on the beam energy and thus the arc voltage. One may also liken the existence of a limiting flow rate to the condition for onset of arc starvation in the duoplasmatron.

The prediction that the electron temperature reaches a maximum value at the limiting flow rate and that its value depends on the mechanisms of ion loss, is of importance to the design of sources for multi-charged ions which should operate at the highest possible electron temperature. The limited experimental data presented in section 3 are consistent with this prediction; in particular the variation of yield of N^{4+} and N^{5+} with magnetic field can now be explained. They do not provide, however, an adequate test of the model: this would require direct measurements of the variation of electron temperature over a wider range of parameters.

In the model presented, one neglects ionisation of ions in the plasma. Clearly this may be an oversimplification for sources designed and operated for the production of multiply charged ions. One can extend the analysis using the formalism presented by Fuchs(4), to show that this model is valid at low values of $n_e \tau$ but is not adequate as $n_e \tau$ rises. A complication then arises in that the ionisation mean free path for neutrals becomes less than the discharge diameter, and one must allow for radial density variations. Until a calculation has been made taking this effect into account it is difficult to assess quantitatively the range of validity of the present model.

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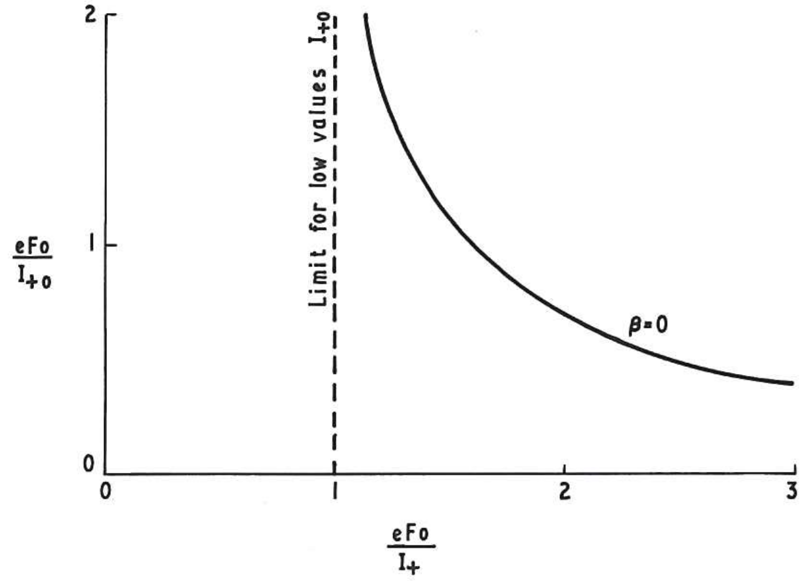

Fig.1 Relationship between the parameter I_{+o}, the gas flow rate and the total ion current (Equation 5).

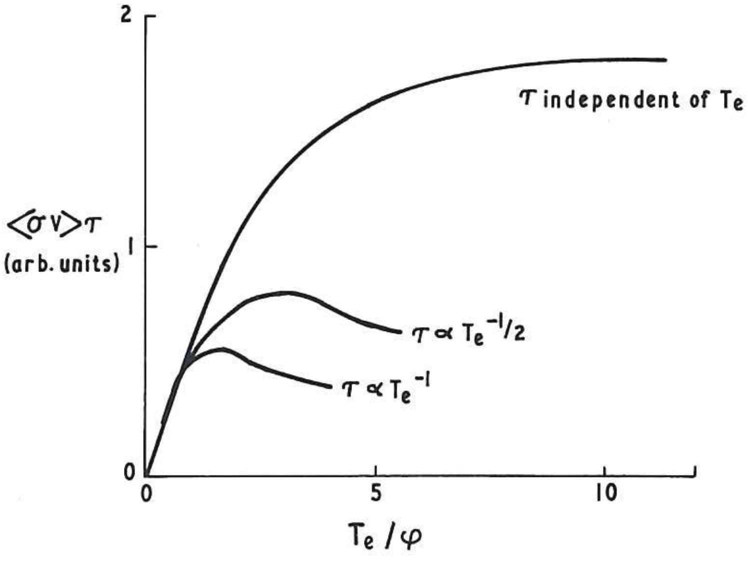

Fig.2 Temperature dependence of the product of the ionization rate coefficient $<\sigma v>$, and the ion containment time, τ.

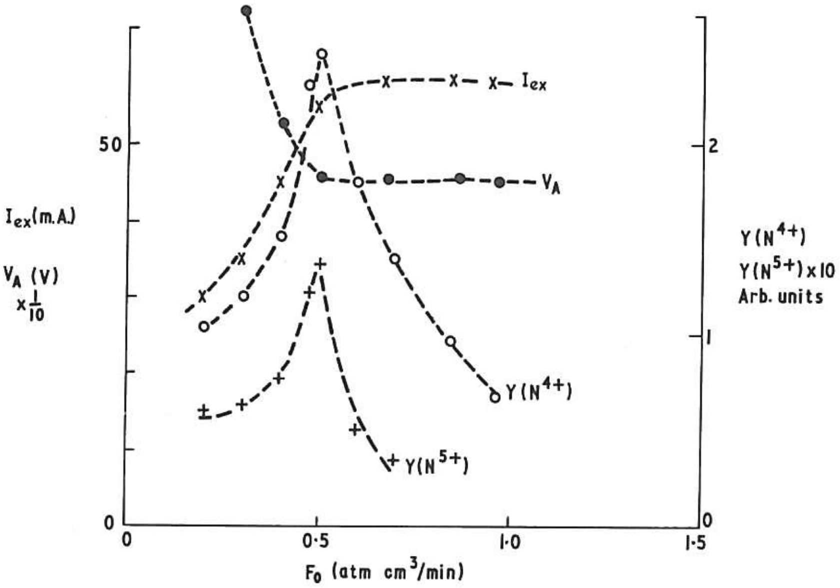

Fig.3 Variation of source performance with gas flow. Data for extraction current I_{ex} arc voltage V_A and yield of N^{4+} and N^{5+} ions.

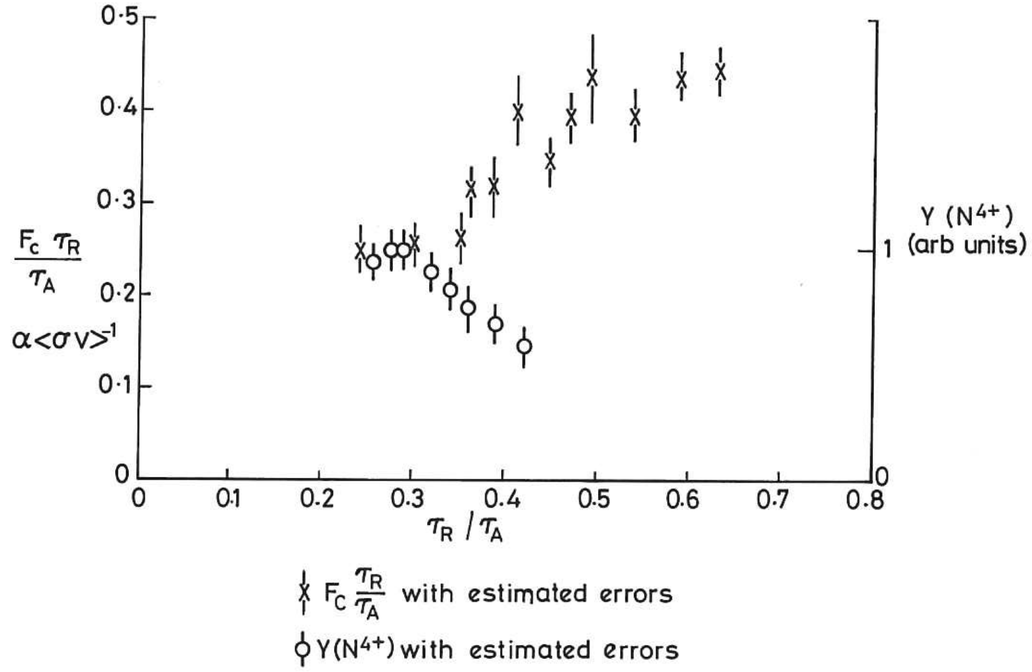

Fig.4 Variation of critical flow rate F_c and yield of N^{4+} ions with ratio τ_R/τ_A.