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Ion source scaling laws

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Abstract. Simple theory and basic plasma physics experiments are used to deduce scaling laws for ion source discharges.

Keywords. Ion sources; plasma discharges.

1. Introduction

Much of the progress made in controlled thermonuclear research can be traced to the advent of intense and effiicient neutral beam injectors. Conversely, these promising results serve to spur on the development of still more efficient sources having improved characteristics.

Despite the considerable worldwide effort there is still only a partial understanding of the impedance characteristics and operating regimes of such ion source devices. The present paper is part of a continuing long range effort to develop scaling laws for the modelling of ion source discharges.

2. The experimental device

The present experiments were performed in the U-2 device (Jones 1980a) (figure 1). The geometry chosen is fairly representative of typical modern ion sources. An array of hot filaments serve as cathode and (one or more of) a plurality of tandem wall electrodes act as anode. The elementary discharge characteristics of the source

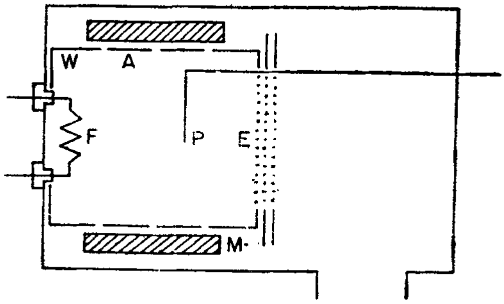

Figure 1. Ion source experiment having filament cathode F, anodes and wall electrodes A and W, Langmuir probe P, possible multidipole magnets M, and extraction grids E.

(but neglecting details due to geometry and electrode biasing) are well understood within the context of zero-dimensional (Jones 1979a) and one-dimensional (Tonks and Langmuir 1929, Jones 1977a) particle and energy balance models while anomalous transport (Jones 1977b, 1980b) and noise (Jones 1978a, 1979b) can be neglected for the present purposes.

Diagnostics consist of Langmuir probes and high resolution planar-gridded retarding field electrostatic energy analyzers (Jones 1978b). The ambient source parameters for the present experiments range according to: $0{\cdot}4<T_i<3$, $1<T_e<15$, $10^8<n_e<10^{12}$, and $10^{-6}<p<10^{-2}$ where T_i and T_e are the ion and electron plasma temperatures respectively (in electronvolts), n_e is the plasma density (in cm^{-3}) and p is the neutral gas pressure (in torr).

Details of the anode (and overall source) geometry and electrical configuration are variable from one ion source design to another and can be neglected when asking certain rather basic questions. Elementary particle balance, for instance, is often obtained under the assumption that the plasma is in contact with a single, uniform, conducting wall (Auer 1961). That is, anode and cathode bias are ignored altogether. While rigorously derivable only for certain RF sustained discharges this model can nonetheless be applied with considerable success (Jones 1977a) to a wide range of devices.

3. Simple zero-dimensional theory

It is well-known that for gas pressures less than some critical value no discharge can be struck (or sustained) at all (Bohm 1949). This behaviour holds true over quite a range of electrode geometries and electrical circuitry and biasing. Minimum operating pressures are now understood for ion source plasmas sustained solely by secondary (plasma) electron-gas ionization (Jones 1978c, 1979b). Primary electron sustained discharges also have critical gas pressures (which are lower still), however, and this limitation has remained a mystery for some years now. (Primary sustained discharges having ionization mean free paths exceeding the plasma dimensions are often preferred because of the high degree of plasma homogeneity (Jones 1980c) and, thence, low ion beam energy spread that results.)

We have been assuming that the source discharge has a filament cathode which emits a surplus of (primary) electrons into the surrounding ionizable gas. The space charge limitation of this electron emission current density J_e is then relaxed by the addition of plasma ions into the plasma-filament sheath. According to Tonks and Langmuir (1929):

$$J_e/J_i \leqslant (m_i/m_e)^{1/2}, \tag{1}$$

where J_i is the ion current density entering the sheath. This relation has been verified repeatedly. For a recent example, under similar plasma conditions, Stenzel (1978) may be referred to.

The total ion current flowing in the source I_i is limited by the gas ionization rate (Stirling *et al* 1979):

$$I_i = Z\sigma n_n\, I_e \frac{V}{A}, \tag{2}$$

where Z is the ionic change, σ is the electron-gas ionization crosssection, n_n is the neutral density (in cm^{-3}), I_e is the total primary (ionizing) electron current, A is the discharge area and V is the discharge volume. We assume here that the discharge is sustained solely by monoenergetic primary electrons (Jones 1978c). Pressure limitation for discharges sustained by thermal (plasma) electrons has been tieated in previous publications (Jones 1978c, 1979a).

As the gas pressure is reduced, the plasma ion density drops, the filament sheath expands, the plasma potential becomes negative (with respect to the wall, figure 2), and the ion flow is directed towards the (more negative) filament cathode. Relating $J_{e,i}$ and $I_{e,i}$ *via* a common sheath area and combining (1) and (2), we obtain (for $Z=1$) the neutral density limitation:

$$n_n \geqslant (m_e/m_i)^{1/2} \frac{A}{\sigma V}, \tag{3}$$

which indicates how the discharge (electrode) area establishes the low pressure operating limit.

Equation (3) has been compared with experiments conducted in a number of gases and for several electrode configurations. The comparisons (table 1) are reasonably close considering the simplifications made in the theory and the usual experimental uncertainties.

For higher neutral pressures, the plasma density and available ion beam current at first increase (as suggested by equation (2)). As the ionization mean free path drops (to values less than the plasma dimensions), however, the plasma density and homogeneity again deteriorate. (High neutral pressure also enhances the magnetic cusp leak width and hence, particle losses.)

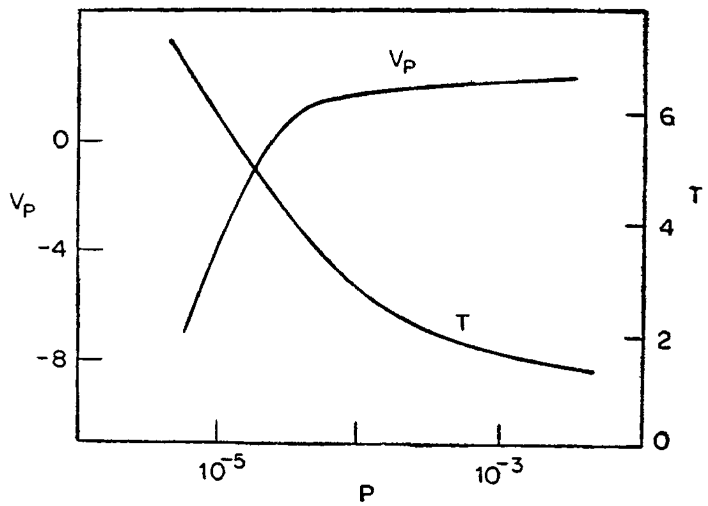

Figure 2. Electron temperature T (in eV) and plasma potential, V_p (in volts) as a function of neutral pressure P (in torr).

Table 1. Discharge neutral pressure limitation.

Gas	Wall area (cm^2)	Ionization cross-section (cm^2)	P_{min} (theory, torr)	P_{min} (experiment, torr)
Argon	300	3×10^{-16}	8×10^{-5}	2×10^{-5}
Argon	10 (effective)	3×10^{-16}	3×10^{-6}	1×10^{-6}
Helium	300	5×10^{-17}	3×10^{-4}	1×10^{-4}
Helium	10 (effective)	5×10^{-17}	1×10^{-5}	1×10^{-5}
Hydrogen	10 (effective)	7×10^{-17}	1×10^{-5}	7×10^{-6}

Source volume = 2000 cm^3

4. Model of the double anode discharge

Many ion sources make use of multiple anodes of differing size and/or electrical bias potential. We have studied such discharges in their archetypal form, the 'double anode' discharge. (The 2 anodes having areas A_A and A_s, respectively.) (generalization to N anodes is straightforward).

For equal 'effective electrode areas' (physical size plus the effect of any magnetic insulation) the most positively-biased electrode fixes the plasma potential (at the electrode voltage plus a few T_e). For unequal effective electrode area, however, a non-trivial problem results, provided that the smaller 'anode' is the more positively-biased (this problem was qualitatively discussed in Tonks and Langmuir 1929). In this case, the plasma potential may fall somewhere between the potentials of the various electrodes ('anodes').

In the presence of only one single (large) anode (defined, conventionally, as the zero of voltage) the plasma will assume a space potential V_p which is some few T_e positive with respect to the anode. This potential difference will assure that electrons are electrostatically confined and maintain discharge neutrality. A small 'auxiliary' electrode can be added and, so long as it is biased negatively with respect to the large anode, will have little influence on the discharge.

If, however, the (small) auxiliary electrode is biased very positively it will act as an effective electron sink despite its small area A_s. Assuming a Maxwellian distribution, the electron current flowing to this 'auxiliary anode' will be approximately

$$e\, n_e(T_e/2\pi m_e)^{1/2} A_s\left(1 + \frac{eV_s - eV_p}{\alpha T_e}\right), \quad 1 \leqslant \alpha \leqslant 2, \tag{4}$$

where V_s is the bias voltage (positive) placed on the auxiliary anode.

The first term in the second set of brackets in (4) accounts for the usual electron saturation current. In ideal theory, the second term would not appear. In most real plasma electrode experiments, however, the electron current does not saturate but continues to rise following a roughly linear dependence on bias voltage. This is discussed in Taylor and Leung (1976) and Spalding (1970). For the present experiment (with small auxiliary anode), this current-voltage relationship has been verified experimentally (figure 3). At the same time, the electron current flowing to the large anode will be limited to:

$$e\, n_e (T_e/2\pi m_e)^{1/2} A_A \exp(-eV_p/T_e), \tag{5}$$

where A_A is the area of the large anode and its potential is again defined to be zero. To maintain charge neutrality in the source, these two currents (equations (4) and (5)) must balance the ion current:

$$\beta\, Z\, e\, n_e\, (2T_e/m_i)^{1/2} A_A, \tag{6}$$

with β a constant of order 1. (We assume that the cathode area is much less than A_A and that the auxiliary anode is too positive to collect ions.) Combining (4), (5) and (6) and assuming that β and $Z=1$, we obtain:

$$A_A(4\pi m_e)^{1/2} = m_i^{1/2} \left\{ A_A \exp(-eV_p/T_e) + A_s\left[1 + \frac{e(V_s - V_p)}{\alpha T_e}\right]\right\}. \tag{7}$$

We can see from (7) that as V_s increases the plasma potential, V_p must also increase. Physically, as the auxiliary anode becomes more positive, the plasma potential must rise also in order to maintain a satisfactory overall electron confinement.

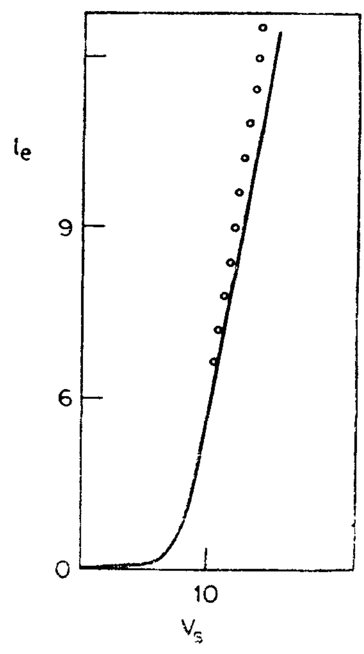

Figure 3. Electron current I_e (in mA) drawn to a small auxiliary electrode as a function of electrode (positive) bias voltage V_s. Solid curve: experiment. Dotted curve: theory equation (4), $\alpha = 1$.

5. Experimental observations

We have sought to verify the behaviour of (7) experimentally. The filament cathode was biased 50 volts negative and the entire source wall served as the large grounded anode. A small 4 cm square tantalum plate was immersed in the centre of the plasma and served as the small, variably biased, auxiliary anode. The current flowing to the large anode (source wall) remained roughly constant at 4.4 amperes as the auxiliary anode voltage was adjusted.

Langmuir probe observations of the plasma were made as a function of bias on the auxiliary anode (figure 4). Negative biases on the auxiliary anode had no effect on the plasma whatever. As the bias exceeded a few T_e positive with respect to ground, however, the plasma potential began to rise. The current to the auxiliary anode (4) also rose with the bias, as indicated in figure 4. Clearly, the auxiliary electrode is beginning to share in the role of current collector and is altering the plasma potential as predicted by eq. (7).

In table 2, we compare the observed values of eV_p/T_e with those computed from (7). Just as in conventional single anode discharges (Liu 1974), the theory overestimates the experimental values somewhat (perhaps attributable to primary electron injection).

We have also investigated the impedance characteristics of the dishcarge by varying the arc voltage while keeping the filament (heating) current and neutral gas pressure fixed. Results were obtained for several different anode areas in a magnetic field free discharge (figure 5) and for a single anode arrangement but with variable multidipole confining magnetic field (figure 6). In the later case, the anode area is given approximately by the ion gyroradius multiplied by the total cusp length (Jones 1979c; Stirling *et al* 1979; Pechacek 1980).

Small effective anode areas are desired in order to reduce parasitic energy, primary

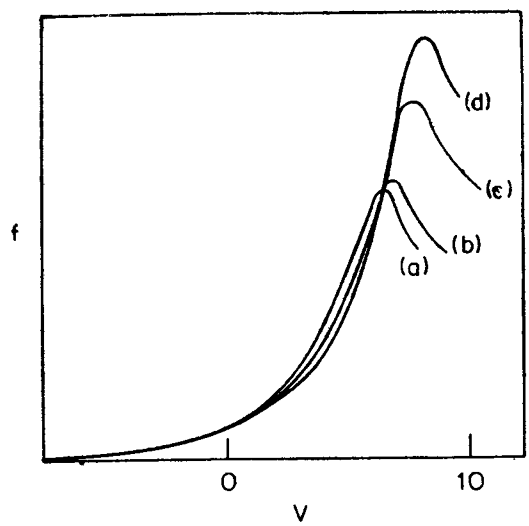

Figure 4. Differentiated Langmuir probe characteristics (f versus probe voltage V) obtained in the source plasma for various values of auxiliary anode bias. Auxiliary anode bias; a = between − 50 and 0 V, b = +20V, c = +35V, d = +37V. Auxiliary anode current: a = <1 mA, b = 10 mA, c = 40 mA and d = 53 mA.

Table 2. Plasma potential variation.

V_s (volts)	$e(V_s - V_p)/T_e$ (experiment)	$e V_p/T_e$ (experiment)	$e V_p/T_e$ (theory)
20	7	3	5
35	14	3·5	7
37	15	4	8·8

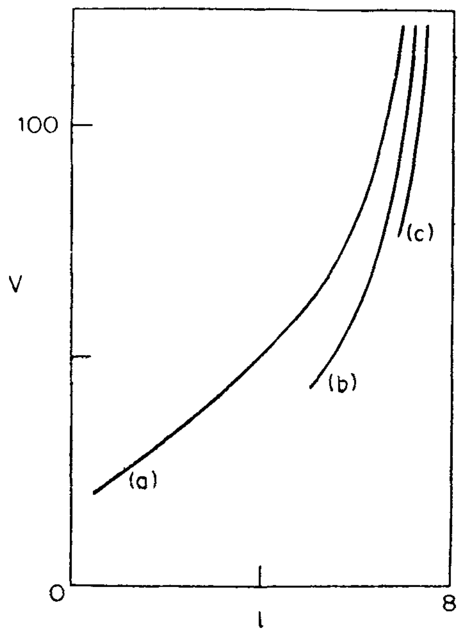

Figure 5. Arc current I (in amperes) as a function of arc voltage V (in volts). Anode area: a = 80 cm², b = 30 cm², c = 15 cm². Source volume = 2000 cm³.

electron and plasma loss. In the multiple electrode source configuration, a small anode can be held positive to control the plasma potential (which must be positive with respect to the outside world if ions are to be extracted) while the walls proper are biased negatively to repel electrons. Unfortunately, for the smallest anode areas investigated experimentally discharges could only be struck (or maintained) at relatively high arc voltages (anode-to-cathode voltage drop). The high voltage portions of figures 5 and 6 are emission-limited (the filament heating being fixed) while the lower voltage operating region (where accessible, for large enough anode area) is the space charge limit studied by us previously (Jones 1978c).

For small anode area low discharge voltage results in zero ion extraction. This is shown in detail in figure 7 where the minimum permissible arc voltage is displayed as a function of neutral pressure. Similar curves are generated when we regulate (fix) the arc current (or, alternatively, the ion beam current) at some (arbitrary) value and measure the arc voltage drop observed as a function of gas pressure (figure 8).

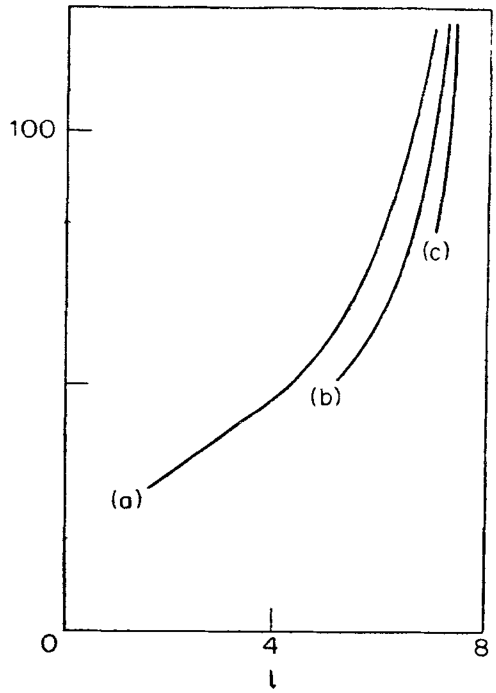

Figure 6. Arc current I (in amperes) as a function of arc voltage V (in volts). Effective anode area: a = 75 cm², b = 30 cm², c = 15 cm². Source volume = 2000 cm³.

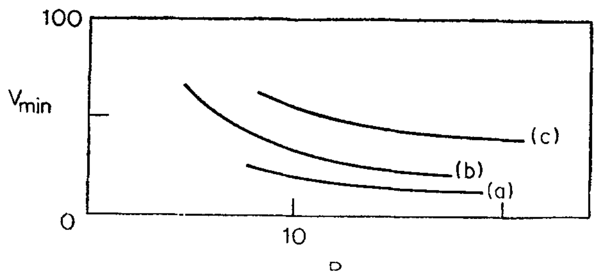

Figure 7. Minimum arc voltage V_{min} (in volts) as a function of source neutral gas pressure P, (in mtorr) Anode area: a = 30 cm², b = 25 cm², c = 1 5 cm².

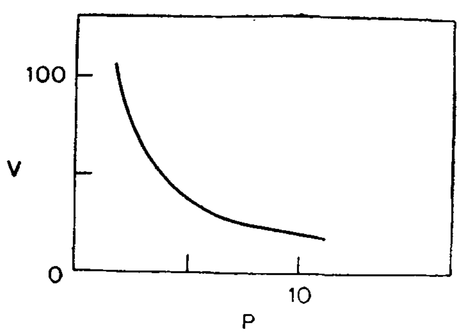

Figure 8. Observed arc voltage V (in volts) at constant arc current (I = 3 amperes) as a function of source neutral gas pressure P, in mtorr. Anode area = 50 cm².

6. Anode area limitation model

It is common practice to bias the source wall negative, in order to maximize electron confinement, and use (as small as possible) a positive anode V_s, A_s to maintain $V_p > 0$ (as required for subsequent ion extraction from the source plasma to an outside world at ground potential).

We can treat this problem using (7) (assuming $V_s > V_p$) where the wall (including ion beam area) is identified as A_A and is biased sufficiently negatively so as to repel primaries (and thence, plasma electrons as well). Under this assumption, the current of eq. (5) is neglected and (7) simplifies to (keeping β and Z):

$$\beta Z\left(\frac{4\pi m_e}{m_i}\right)^{1/2} A_A = A_s\left[1 + \frac{e(V_s - V_p)}{\alpha T_e}\right]. \tag{8}$$

Combining this with our requirement for beam extraction:

$$V_p > 0, \tag{9}$$

we obtain:

$$\frac{A_s}{A_A} > \frac{\beta Z(4\pi m_e/m_i)^{\frac{1}{2}}}{1 + (e V_s/\alpha T_e)}, \tag{10}$$

(but not so large as to violate $V_s > V_p$).

Equation (10) is in qualitative agreement with figure 7. A minimum anode area A_s, is observed experimentally and this limitation is relaxed as the arc voltage (and hence V_s) increases. A pressure dependence (figure 7) is not contained explicitly in the model but it is known, experimentally (figure 2), that T_e (in eq (10)) varies inversely with gas pressure so that a pressure increase can play the role of an increase in V_s (in agreement with figures 7 and 8). (For fixed discharge parameters I_e power P, ionization energy E_I, etc., simultaneous particle,

$$e A n_e\left(\frac{T_e}{m_i}\right)^{1/2} = \sigma\, n_n\, I_e \frac{V}{A}, \tag{11}$$

and energy balance,

$$P = A n_e\left(\frac{T_e}{m_i}\right)^{1/2}(E_I + eV_p + 2T_e), \tag{12}$$

predict such a dependence of T_e on n_n:

$$\frac{1}{n_n} = (2T_e + eV_p + E_I)\left(\frac{\sigma I_e V}{e P A}\right), \tag{13}$$

(Jones 1979a). We have assumed here that the neutral density is an independent, externally controlled variable. At very high powers, however, neutral penetration of the plasma becomes difficult, 'arc starvation' sets in, and the neutral density in the plasma core drops. This, in turn, allows a core electron temperature rise.

7. Conclusions

Simple theory and basic plasma physics experiments have been used to deduce some scaling laws for ion source discharges. The Langmuir sheath stability equation and the gas ionization rate combine to impose a limitation on the neutral fill pressure. The detailed result is verified experimentally. This pressure limitation in turn combines with power and particle balance to impose restraints on electron plasma temperature.

The origin and importance of anode area limitation is pointed out and a model of the double anode discharge is formulated and compared (qualitatively) with experiment.

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