CHARACTERISTICS OF A HIGH CURRENT P.I.G. ION SOURCE AT LOW GAS PRESSURE

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Summary

The characteristics of a 10 cm P.I.G.(Penning ionization gauge) discharge and its application as an ion source at a low pressure are given. Using a hot cathode two regions of operation are found, one above and the other below 1 micron. Pulsed ion current reaching 1 Ampere could be extracted from this source through a 10 cm diameter gridded cathode at a discharge current of about 20 Amperes and a gas pressure of 0.5 micron. The cathode discharge current was found to contain electrons. The ion current to the reflector cathode is about 10% of the discharge current.

1. Introduction

There has been increasing interest in high current ion sources for their use in intense injectors for accelerators, ionic propellers and for thermonuclear research. In all types of intense sources it is always necessary to create a region of high ionization density and to furnish some means for the extraction of ions from such ionized region. Furthermore it is essential to achieve this with the maximum possible efficiency of gas and electrical power consumption. It is equally important that the beam be extracted with maximum percentage of atomic ions, both for beam homogenity and for improved efficiency.

The mechanism for producing an intense plasma varies from one type of ion source to the other, while ion beam extraction is usually effected by a highly negative extractor that produces the required shape and strength of the extraction field. In the P.I.G. ion source use is made of electron oscillation between two cathodes, and a magnetic field that reduces their diffusion out of the plasma and thus the electron mean lifetime is increased resulting in a dense plasma with a low pressure. The advantage of obtaining a high beam current at low pressure is obvious since the ratio of ion to neutral flux will be large and thus a high gas efficiency could be achieved.

In this work the discharge mechanism and extraction phenomenon are described. Effect of secondary electron emission whithin the source and out of it on the beam collector is considered. Also, the positive ion division between the cathodes is discussed, and this is compared with the experimental values obtained. Another comparison is made between the extracted current and that calculated from the Child-Langmuir law.

2. Mechanism of the P.I.G. Ion Source

The P.I.G. Discharge.

In the P.I.G. discharge electrons oscillate between two plane cathodes separated by a cylindrical anode in the presence of an axial magnetic field which confines electrons and prevents them from escaping to the anode. Hence the increased lifetime of electrons raises their probability of ionization and a dense plasma is formed at a reduced pressure. During their oscillation electrons make elastic and ionizing collisions with gas molecules. The resulting ions are transported equally to both cathodes under ideal symmetry and eject secondary electrons from the cathodes which oscillate like the primary electrons and take part in the ionization processes. The secondary electron current depends on the ion energy, the cathode material and its surface conditions. It is given by γI^+, where γ = secondary emission coefficient, and I^+ = positive ion current to the cathode.

Now, due to electron collision with gas atoms and molecules, they will diffuse across the magnetic field to the anode where they are collected to return to the power supply. However, the two-body collision diffusion is not enough to account for the entire discharge current. Thus, there must be another diffusion mechanism. It is possible that when electrons move in crossed electric and magnetic fields a cycloidal motion will result giving electrons an average drift velocity perpendicular to both fields. This transverse drift velocity is given by[1]

$$V_D = \frac{10^8 E}{B} \qquad (1)$$

where B is the magnetic field (gauss), and E is the component of electric field perpendicular to the magnetic field (V/cm). Bohm[2] found that such motion is unstable and is rich with every type of oscillations. Because the plasma oscillates, electric fields can arise which could produce a motion of electrons perpendicular to the magnetic field. Thus it is perhaps not surprising that we observe oscillations in practice.

The Ion Extraction from the Plasma.

It is well known that most plasmas or plasmas in thermionic equilibrium are surrounded by a positive ion sheath which exists between the plasma boundary (S_1 in Fig. 1a) and any surface S_2 near the plasma. This surface is charged negatively and the plasma assumes a positive potential with respect to the surface. For a plane electrode the sheath thickness is given by[3]

$$t = 0.23\, V^{\frac{3}{4}} / M^{\frac{1}{4}} (j)^{\frac{1}{2}} \quad \text{cm} \qquad (2)$$

where M = molecular weight of the gas, V=potential difference across the sheath (volts) and j=ion current density leaving the plasma boundary (A/cm^2) and is given by

$$j = 3.5 \times 10^{-10} n^{+} (T_e^{\frac{1}{2}} / M^{\frac{1}{2}}) \qquad (3)$$

where n^+=positive ion density, and T_e=mean electron temperature.

If a circular hole is cut in S_2 (Fig. 1b) the plasma penetrates through the hole. This part of the plasma becomes the ion-emitting surface when the appropriate negative potential is applied to the extractor S_3 (Fig. 1c). Under the most favourable conditions a parallel beam is emitted whose current is space charge limited given by the Child-Langmuir law[4]

$$J^{+} \text{ (protons)} = 5.46 \times 10^{-8} \frac{V_{ex}^{3/2}}{X^2} \text{ A/cm}^2 \qquad (4)$$

where V_{ex}=extraction voltage (volts), and X = extraction gap (cm). The electric field in the extraction gap is obtained from eq.4.

$$\frac{dV_{ex}}{dX} = E = 5600 \quad I^{\frac{1}{2}} \; S^{-\frac{1}{2}} \quad V_{ex}^{\frac{1}{4}} \qquad (5)$$

Where I = total beam current and S = area of ion-emitting surface. Eq.5 indicates that the electric field could be reduced by increasing the area of plasma boundary, thus reducing the voltage breakdown problems.

The different systems which could be used for beam extraction are indicated in Fig. 2. With a Pierce[5] extractor a concave plasma boundary could be established (Fig. 2a) with the proper extractiin voltage. The emission area is higher than that of a flat boundary. Still higher ion currents could be extracted by using an expansion cup (Fig. 2.b) whereby the plasma protrudes through a narrow aperature which restricts the gas flow, a larger plasma boundary is formed on the application of V_{ex} to an extractor in the form of a cylinder or a grid[6,7]. Another method for ion extraction is to use grids in S_2 and S_3 (Fig. 2c), this is the method used here.

3. Experimental Work and Results

Apparatus Description.

The P.I.G. ion source used in these experiments is shown in Fig. 3. The copper anode "A" and the top cathode "C" are water cooled. The reflector cathode "R" is a tungsten grid 88% transparent. Hydrogen is admitted through a nickel leak via a hole in the top cathode. The emitter is prepared by coating a strip of nickel gauze with a mixture of 80% nickel powder, 10% barium carbonate and 10% strontium carbonate. The extraction electrode has a grid identical to that of the reflector and is aligned by three adjustable screws. An insulated platform carries the source's supplies which are fed through an isolation transformer. A 20 A delay line supplies the anode with up to 200 V pulses.

Dependence of Arc Current on the Pressure.

The gas pressure is measured by an ionization gauge corrected for hydrogen, while the peak arc current is measured on the oscilloscope using a 0.1 ohm resistor in series with the cathode. With a fixed arc voltage of 80 V and filament current of 51 A, the magnetic field is optimized at each point as shown, in Fig. 4. We have two distinct regions in the low pressure range; one below 1 μ, and the other above 1 μ with a higher slope. It is also seen that the optimum magnetic field decreases with pressure increase.

Measurement of the True Ion Current.

Another tungsten grid 10 cm diameter and 88% transparency is negatively biased to eliminate errors due to secondary electrons emitted from the ion collector. The entire system is shielded with a grounded cylinder (Fig. 5). With an extraction voltage of 3.2 kV the collected ion current I_c is seen to decrease with the bias voltage until all secondary electrons are returned and I_c is saturated (Fig. 6). In this region the suppressor grid current I_B increases slightly since all secondary electrons, and thus the part intercepted by the grid, are returned to the collector. In the plateau region the true ion current $I_T = I_c + I_B = 0.625 + 0.45 = 1.075$ A. In this calculation the effect of secondary electrons from the grid has been neglected. From this we can estimate the secondary emission coefficient γ at V_{ex}=3.2 kV,

$$\gamma = \frac{\text{secondary electron current}}{\text{primary ion current}} = \frac{1.1-0.625}{0.625} = 0.76$$

When the experiment was repeated at 2 kV, γ was found to be 0.49.

Extraction Characteristics.

This is obtained at a pressure of 0.5 μ (other parameters as shown in Fig. 7). The true ion current starts to saturate at about 1 kV extraction voltage (curve 2). The secondary electron current (= difference between curves 1 and 2) increases with the extraction voltage since γ increases with the energy of primaries as shown in Fig. 7', curve 2, calculated from Fig. 7. These results agree reasonably well with results obtained by other workers[8] (curve 1 Fig. 7').

The Ion Current to the Cathodes.

The ion current to the top cathode I_P and that to the reflector cathode I_R are measured at a pressure of 0.5 μ, a filament power of 128 W, magnetic field of 22.5 G, and an extraction voltage of 1.5 kV. The extracted true ion current I_T (V_{bias} = 120 V) is also measured at different discharge currents, (Fig. 8). It was noticed that with V_{ex} = 0 an appreciable electron current I_e reaches the collector.

These results indicate that this source is asymmetric as $I_p \gg I_R$. This is in contradiction with the idea that half of the discharge ions go to each cathode[9]. The ion current to the reflector cathode is about 9% of the discharge current under these conditions.

Discussion of the Results.

From eq. 1 the space charge limited current is calculated and is compared with the extraction characteristics (true ion current). The agreement is only satisfied around 1 kV (Fig.9). At lower voltages the experimental current is higher than the calculated values. This is due to plasma penetration through the reflector grid at lower voltages thus reducing the gap distance. The experimental current then saturates at higher voltages to a value of about 0.6 A. At higher voltages, however, the plasma boundary retracts inward and the gap distance increases.

Assuming that the positive ion current is divided between the two cathodes, and considering secondary electron emission from the top cathode while the reflector cathode is regarded as being open (88% transparency) then the discharge current will be, $I_d = I^+ (1 + \gamma') + I^+$, where γ' is the secondary emission coefficient of copper for slow ions in hydrogen ($\gamma' = 0.05$). Thus the positive ion current to each cathode is

$$I^+ = \frac{I_d}{2+\gamma'} \qquad (6)$$

For a discharge current of 10 A (corresponding to a true value of ion current of 0.6 A), I^+ from eq. 6 will be 4.88 A. By considering the 88% transparency of both reflector grid and suppressor grid I^+ should be 3.78 A, which is much higher than 0.6 A. This deviation is explained as follows. When the magnetic field is sufficiently strong an intense negative space charge is formed at the discharge axis causing a reduction of the axial potential and allowing some electrons to reach the cathode and cancel a large part of the positive ion current. This is confirmed by the electron current indicated by the collector when the extraction voltage is zero (I_e in Fig. 8). For I_d = 10 A, I_e reaches more than 2 A. It is therefore seen that the discharge current as measured in the cathode circuit contains an electron current component due to the negative space charge, which agrees with previous observations[8,10].

On the other hand the current I_p to the top cathode is $\gg I_R$ of the reflector cathode (Fig.8) due to the contribution of electron current leaving the filament as well as secondary electron emission from the entire area of the top cathode surface.

As shown in Fig. 8, it is reasonable that the reflector current I_R is approximately equal to the true ion current I_T which is extracted through this cathode.

Acknowledgements.

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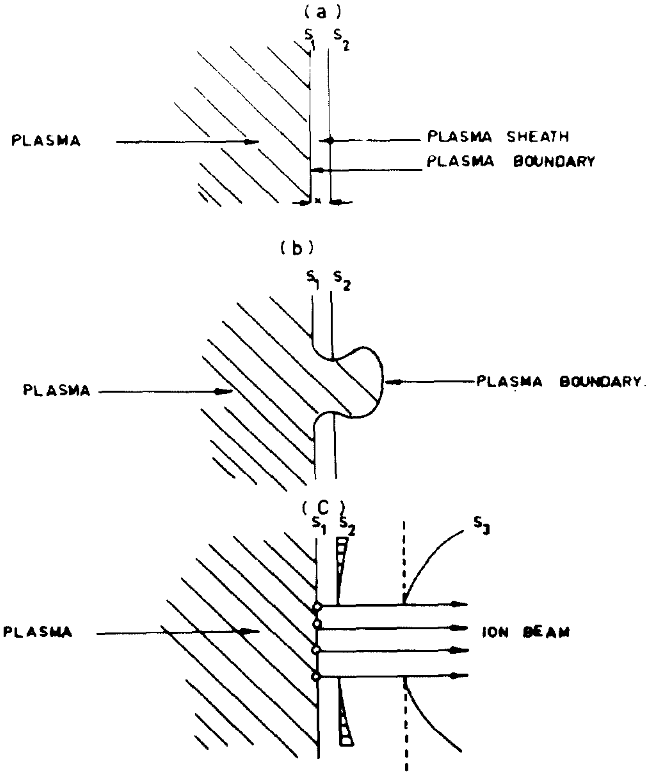

Fig. 1. The Ion Extraction from the Plasma.

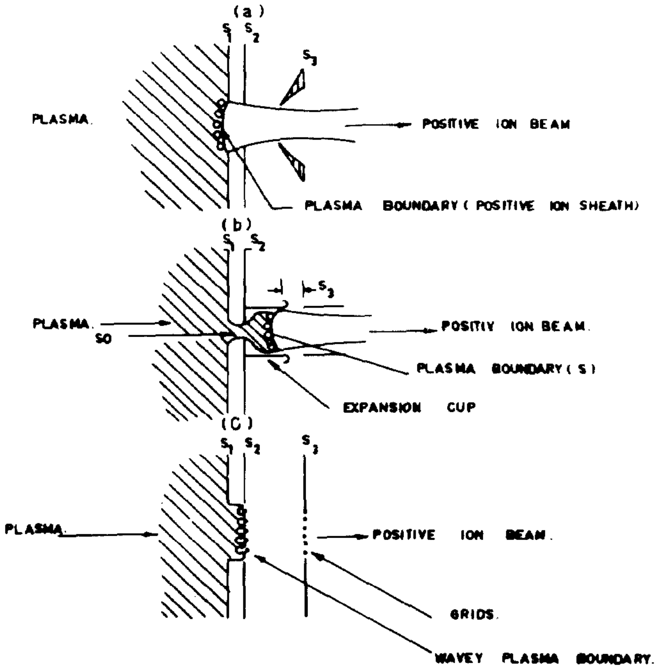

Fig. 2. The Ion Extraction from the Plasma.

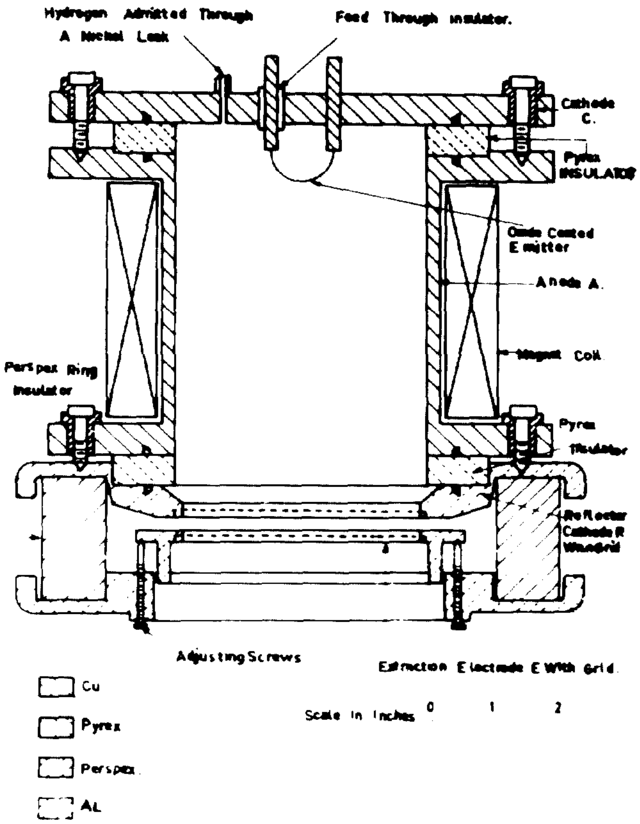

Fig. 3. A Cross-Sectional View of the P.I.G. Ion Source Assembly.

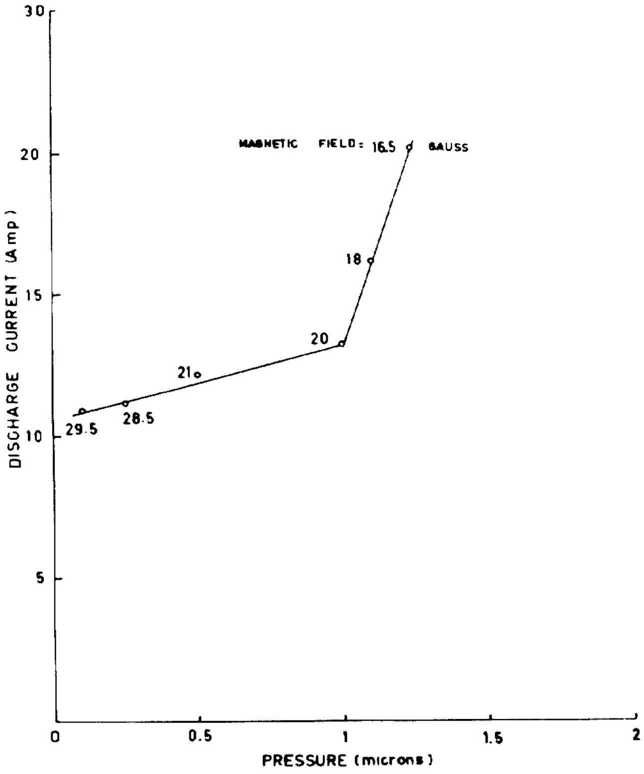

Fig. 4. Variation of the Discharge Current with the Pressure, the Magnetic Field Varies as shown on the Curve.

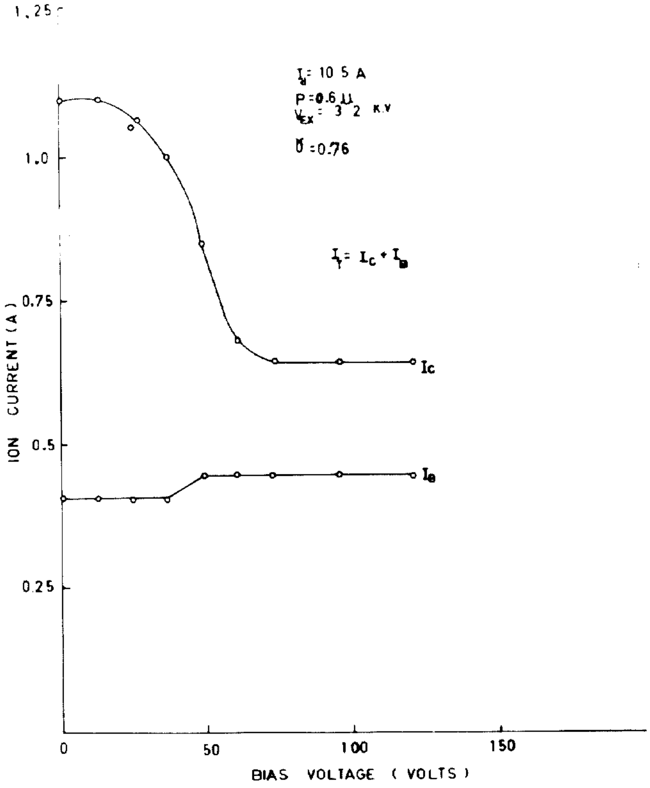

Fig. 6. The True Ion Current.

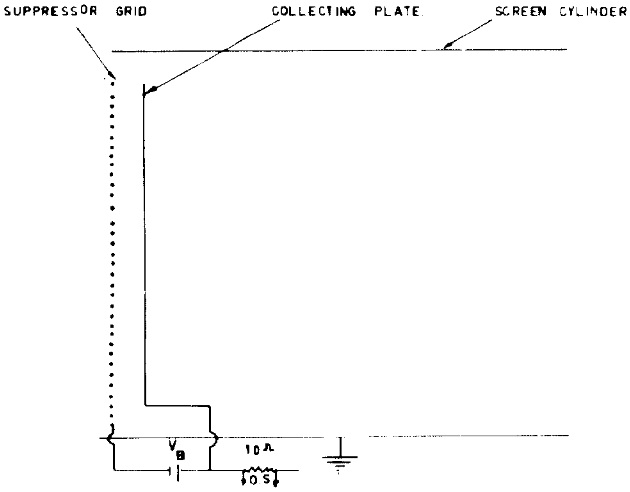

Fig. 5. Electrostatic Suppression of Secondary Electrons for Ion Current Measurement.

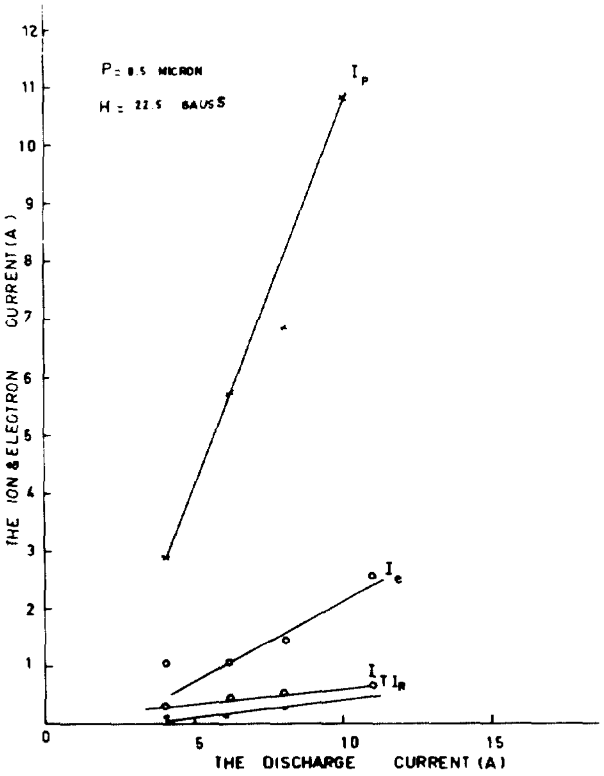

Fig. 8. The Ion Current to the Cathodes.

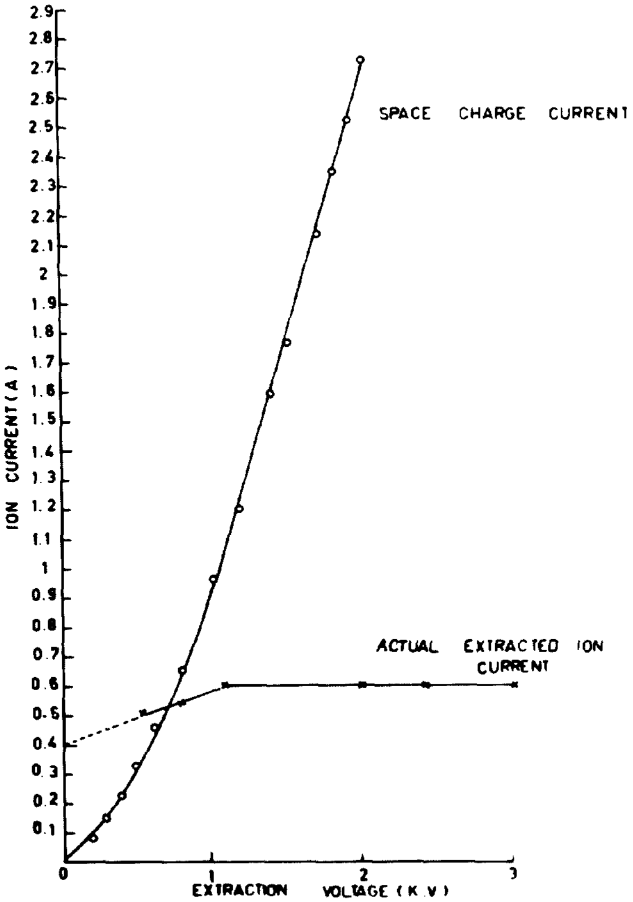

Fig. 9. Comparison between the Space Charge Current and the Actual Extraction Ion Current.