A STUDY OF A DUOPLASMATRON ION SOURCE WITH AN EXPANSION CUP

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Summary

This work describes a study of the Duoplasmatron ion source for the purpose of investigating the conditions necessary to improve its performance. First a general review is made of theoretical considerations involved in the source's plasma mechanism and the geometry of the extraction system. Then the experimental work deals with the arc discharge characteristics as well as the source's performance when the beam is extracted with a simple Pierce extracting electrode. Through an invar anode insert a 70 mA was obtained at 35 kV. The main improvement was then due to beam extraction from an expansion cup which rendered a 300 mA beam at a lower voltage of 18 kV.

The use of different anode materials has indicated the influence of magnetic field penetration on plasma focusing within the expansion cup. A beam current reaching 1 ampere was noticed when a non-magnetic anode was used.

1. Introduction

Recent developments on high current accelerators for nuclear disintegration, ion injectors for thermonuclear research and ionic propellers for space vehicles have stimulated deep interest in the study of high current ion sources. Among the different types of intense ion sources in use today, the Duoplasmatron is featured with its high ionization efficiency, high current density and the possibility of yielding a beam with a reasonably good quality due to the focusing properties of its extraction system.

Since the first type of Duoplasmatron was introduced by von Ardenne[1] many subsequent developments have been mainly concentrated on its extraction system which is certainly the most critical in ion source design. However, for the extracted beam to contain a high current density it is also essential that the source's plasma has to be sufficiently rich with ionization densities so that it could supply the ion emitting surface with the required current density. The mechanism by which intense ionization is produced within the arc chamber of the Duoplasmatron makes it unique in satisfying such requirements.

Consequently a review is first made of the theoretical considerations connected with the two main problems of the source, i.e. the plasma theory and the theory of ion beam extraction. This is followed by an experimental investigation of the source's performance, also on the two main problems. Thus, the arc discharge and ion-beam extraction characteristics are obtained experimentally under different conditions. Interpretation and analysis of these results is based on the theoretical studies presented here.

2. Theory of the Duoplasmatron Ion Source.

In the basic Duoplasmatron configuration[1] a low pressure arc is produced between a cathode and an anode. A conical intermediate electrode causes mechanical constriction, while a strong magnetic mirror between the intermediate electrode and the anode causes magnetic constriction. Thus a very dense plasma is created in the vicinity of the extraction aperture. Plasma penetration through the anode aperture permits a large area plasma boundary to emit an ion beam on the application of a highly negative potential to the extractor. In the following both problems are treated, namely the plasma theory and that of ion beam extraction.

2.1 Plasma Theory of the Duoplasmatron.

The normal arc discharge (one without constrictions) consists of three regions[2]: the cathode drop with a voltage drop approximately equal to the first ionization potential of the gas. It includes a strong positive charge near the cathode. The positive column, or plasma, exists at a short distance from the anode and is characterized by a small potential gradient and charge neutrality. The third region is the anode drop, near the anode, with a strong negative charge. The cathode electrons acquire enough energy to produce ionization in the positive column. After different collisions they are scattered at random, but due to their higher mobility the electron temperature is higher than the ion temperature. Thus there is no thermal equilibrium between electrons and ions. The electron drift current represents the arc current which is given by[2]

$$I_a = 2.38 \frac{h_o e^2 a^2 n_o \lambda E}{(m_e k T_e)^{1/2}} \qquad (1)$$

where a = discharge radius, n_o=electron concentration at the axis, λ = electron mean free path, E = voltage gradient, T_e = electron temperature, e and m_e are electronic charge and mass resp., k = Boltzman's constant, and h_o is a series that corresponds to a current density.

Ion Sheath Formation: By considering the Langmuir plasma it was found that with a Maxwellian distribution among plasma electrons a stable ion sheath could be formed only when ions reach the sheath with an energy at least equal to half the electron temperature[3]

$$\frac{1}{2} m^+ v^{+2} = e V_o \geq \frac{k T_e}{2} \qquad (2)$$

where m^+ = mass of the positive ion, v+ = its velocity. The ion density at the sheath is then

$$J^+ = n^+ e v^+ = n^+ e \sqrt{\frac{kT_e}{m^+}} \qquad (3)$$

The sheath thickness 't' is regarded as being equal to the Debye length[4]

$$t = 6.9 \left\{\frac{T_e}{n_e}\right\}^{1/2} \qquad (4)$$

indicating that plasma homogeneity, is observed only over regions large compared with 't'. The ion sheath protects the plasma from the walls or electrodes. Thus the electric gradient due to the extraction potential is supported by the sheath and not by the plasma.

Effect of Magnetic Field and Double Layer Formation: With the presence of a strong magnetic field B, the plasma will be confined by a magnetic pressure[5]

$$P = -\frac{1}{8\pi} B^2 \qquad (5)$$

Such confinement will naturally reduce the diffusion losses of ions and electrons. In a magnetic field the diffusion coefficient is given by

$$D \quad \frac{D_o}{1 + (\omega_c \tau)^2} \qquad (6);$$

where D_o= ordinary diffusion coefficient, τ = mean free time of particles, and ω_c = cyclotron frequency.
In addition, the mechanical constriction causes magnetic field shaping as to force electrons to the central part. Frequent collisions with ions occur and the ion temperature will approach the electron temperature. Also, the formation of a hot dense plasma in the anode baffle space causes thermal ionization of any neutral gas particles which tend to escape from the source. This increases the gas ionization efficiency to high values. With this mechanism, we actually have a clear luminuous spherical surface, similar to a fire ball, on the cathode side of the constriction[6]. Instead of the sheath - or monolayer - there will be an electrostatic double layer in the midst of the plasma. Two space charge limited flows exist; one for ions in the cathode direction, and one for electrons in the opposite direction (fig.1). The double layer acts as a quasi cathode to supply the necessary extra electrons to produce the anode arc current. A potential jump exists in the double layer rendering an ionization mechanism in the cathode plasma due both to Townsend ionization and thermal ionization. Electrons will also oscillate up and down this potential hill. The energy required for such plasma oscillations is absorbed from cathode fast electrons. The beam-plasma interaction[6] could yield electrons with up to 1000 eV energy and positive potentials $>$100 V. It could be shown[7] that the discharge pressure p and potential jump V over the double layer are related by the equation

$$V^{3/4} p = \text{constant} \qquad (7)$$

Thus, the heating effect of the "fire ball" gets better for lower pressures until we reach a limit ($< 10^{-2}$torr) when the size of the "fire ball" increases to touch the wall causing sharp reduction of plasma temperature. This loss could be compensated by increasing the filament current, but the efficiency in this case will be lower.

2.2. Extraction of Ion Beams from the Source's Plasma

It is known that the extraction problem is the most critical problem in ion source design. In other types of sources the current extracted from the inside of the source to the external region is monopolar so that space charge effects in the exit aperture are severe. However, in the Duoplasmatron this effect is greatly reduced since a bipolar current, i.e. a plasma, folows out from the anode aperature to a small cup as shown in fig.2. The magnetic mirror enhances plasma penetration to the exit cup. A Pierce type extractor could then be used to extract ions from the expanded plasma boundary possibly in a parallel beam. The beam diameter and angle of divergence depend on the field shape, beam intensity and extraction field strength. The field shape depends on electrode geometry and geometry of plasma boundary. The latter behaves like an elastic membrane balanced on one side by the plasma pressure and on the other by electric field pressure.

When maximum current is extracted from the plasma boundary the beam should be space charge limited given by the Langmuir equation[8] corrected by a factor γ-considering the fringing field for a finite electrode[9]

$$\underset{(\text{amp})}{I} = \frac{5.45 \times 10^{-8}}{\sqrt{M}} A \frac{V_{ex}^{3/2}}{d^2} \gamma \qquad (8)$$

where V_{ex} = extraction voltage (volts), M = molecular weight of ions, A= emission area(cm^2), and 'd' is the extraction gap (cm) which was found to depend on the extraction geometry if we consider plasma penetration as a cone (fig.3)

$$\frac{d}{A^{1/2}} = \sqrt{\frac{\pi}{4}} \left[D - (D - \phi) \frac{d}{\ell}\right] \qquad (9)$$

(D, ϕ & ℓ as shown in fig.3)

From 8 and 9 we get

$$d = \frac{3.7 \times 10^{-2} D \gamma^{1/2} V_{ex}^{3/4} I^{-1/2}}{1 + 3.7 \times 10^{-2} (D - \phi) e^{-1} \gamma^{1/2} V_{ex}^{3/4} I^{-1/2}} \qquad (10)$$

where V_{ex} is in kV. Thus d increases with the extraction voltage.

The minimum ion density required to supply ions to the beam is obtained by comparing eq.3 of the ion density in the plasma boundary with eq.8 to get

$$n^{+}_{min} = \frac{\sqrt{2}}{9\pi (ek)^{1/2}} \frac{1}{d^2} \left(\frac{V^3}{T_e}\right)^{1/2} \gamma \qquad (11)$$

If the available density is $< n^{+}_{min}$ the plasma boundary is pushed backward. In the Duoplasmatron where the ion density could be $> n^{+}_{min}$ the plasma flows out of the aperature (fig.2).

Ion Beam Extraction Using an Expansion Cup: If a metallic cylinder is used at the anode exit (fig.4) , a region is produced in which the extraction electric field is weak. The plasma boundary becomes stable along an equipotential surface and ion emission is space charge limited as its current density will be equivalent to that at plasma boundary. It should be possible[10] by a suitable choice of all parameters to obtain a plane or even a concave plasma boundary, emitting a parallel or even slightly convergent beam. Magnetic field penetration in the expansion cup confines the expanded plasma, reduces its losses to the wall and requires a higher value of V_{ex} to establish an ion emitting surface (fig.4b).

3. Experimental Work

A Duoplasmatron ion source of the von Ardenne type[1] with modifications as introduced by others[12] was used here. Different filament materials were tested, the oxide-coated ones had a longer life. A stainless steel anode with a tungsten insert was used at first. After the extraction of high beam currents the tungsten insert was melted, so it was replaced by an invar insert. Later on a completely steel anode, then a copper anode were used. This was done to study the effect of anode material on magnetic field penetration is the extraction region.

The arrangement of electrical circuits is shown in fig.5. A high voltage platform isolated from ground carries these circuits which are fed through a 150 kV isolation transformer.

The Arc-Discharge Characteristics: A sample is shown in fig.6 indicating the current voltage characteristics corresponding to d.c. operation of the arc at different hydrogen pressures and using a bifilar tungsten filament. The curves start with a positive slope, then come to a saturation region which decreases with reduced pressure until a maximum is obtained. The current-impedance curves (fig.6') deduced from fig.6 show a peak that corresponds to the saturation region which identifies the existance of a resonance, a phenomena similar to the Ramsauer effect[2] Much of the arc properties could be explained by referring to eq.1.Thus , with other parameters fixed, I_a increases with the arc voltage. Also, it increases with λ, i.e. with reduced pressure. This is confirmed by eq.6 where diffusion losses in a magnetic field decrease with reduced pressure, i.e. with increased τ. It is also seen that when V_a is gradually decreased the I_a-V_a curves (dotted lines in fig.6) lie above those when V_a is increased. This is due to the ionization inertia caused by the residual ionization from the previous higher voltage discharge.

The Extraction Characteristics : A 30A delay line pulse generator was used to deliver 200 µs current pulses at a frequency of 1 pps. The Pierce type extracter was designed[13] to yield a parallel beam. The baffle canal of the intermediate anode was 10 mm long, 0.5mm diameter and 2mm far from the anode whose aperture was 0.5mm diameter. With an extraction gap of 4mm the extraction characteristic was obtained at different filament and magnet currents, the magnetic field being optimized in each case. Due to bad alignment the current was very small($<$20mA). After aligning the baffle canal with the anode and the extractor the beam perveance was increased, as the beam current went up to 70mA at the same voltage of 35kV(fig.8).

The effect of arc current on the extracted beam current is shown in fig.9.This is explained by eq.3 indicating the direct proportionality between current and ion densities, and by eq.1 showing direct proportionality between arc current and particle density.

The source's performance was then examined using an expansion cup 6 cm long & 6cm in diameter(fig.4a).Beam extraction was effected by a 90% transparent tungsten grid.The improvement thus obtained is clear from fig.10 where a 300 mA was extracted by less than 20 kV. The voltage breakdown troubles observed earlier were almost eliminated.

When a copper anode was used so that the magnetic field was allowed to diffuse in the extraction chamber a sudden increase of the beam current to 1A corresponding to 25kV was noticed. As explained in sec.2.2 and fig.4b plasma confinement & reduction of ion losses in the expansion chamber must be the cause for this significant improvement. A further,more detailed study of this point is needed.

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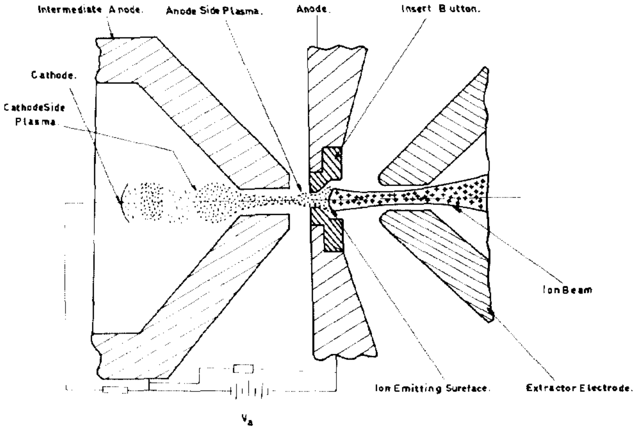
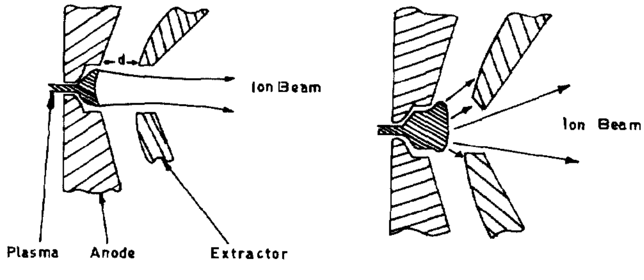


Fig. 1. Arrangement of duoplasmatron electrodes and the cathode side electrostatic double layer.



-a- ni is low.

-b- ni is high.

Fig. 2. The plasma boundary formation.

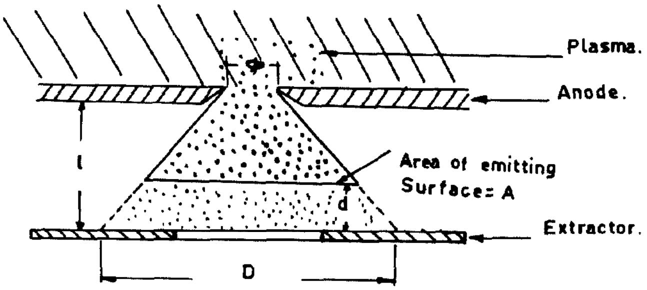


Fig. 3. Arrangement of parallel plane extraction electrodes.

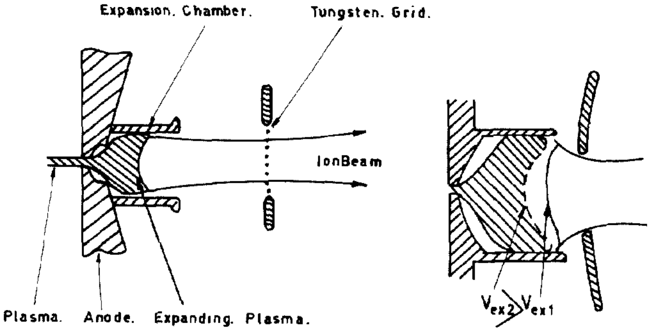


Fig. 4. The extraction system with expanding plasma.

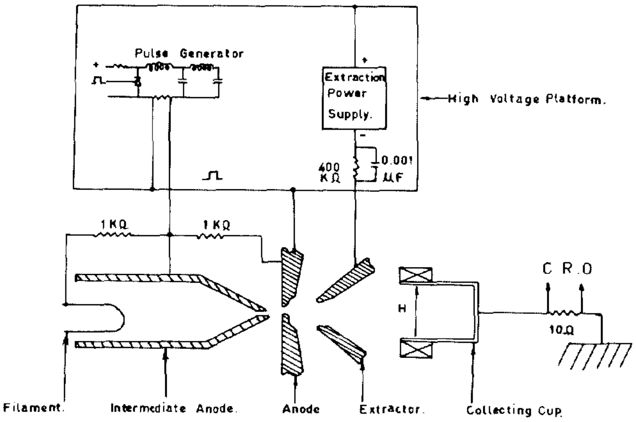


Fig. 5. Schematic diagram of the electrical arrangement.

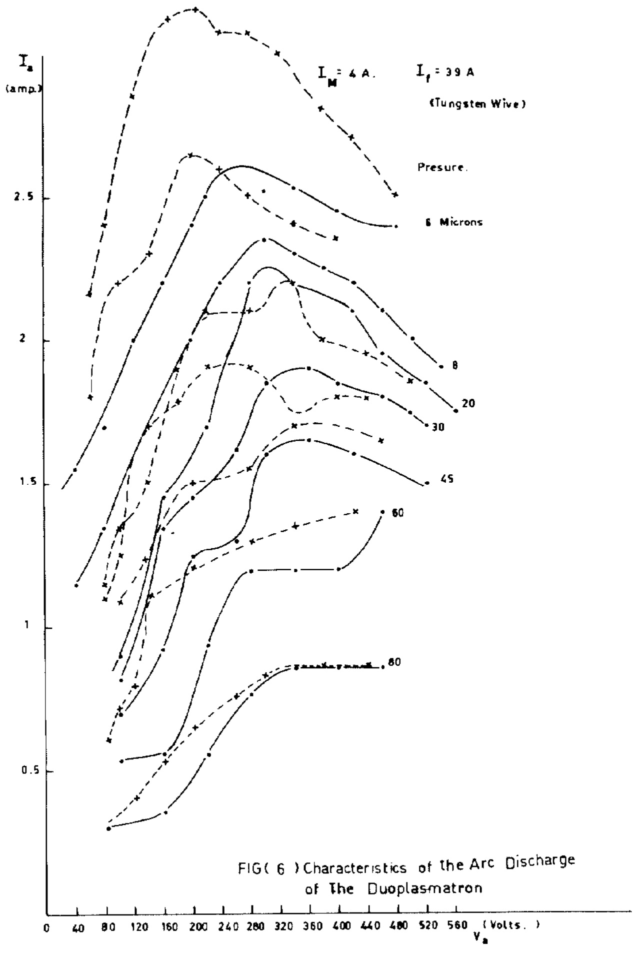


Fig. 6. Characteristics of the arc discharge of the duoplasmatron.

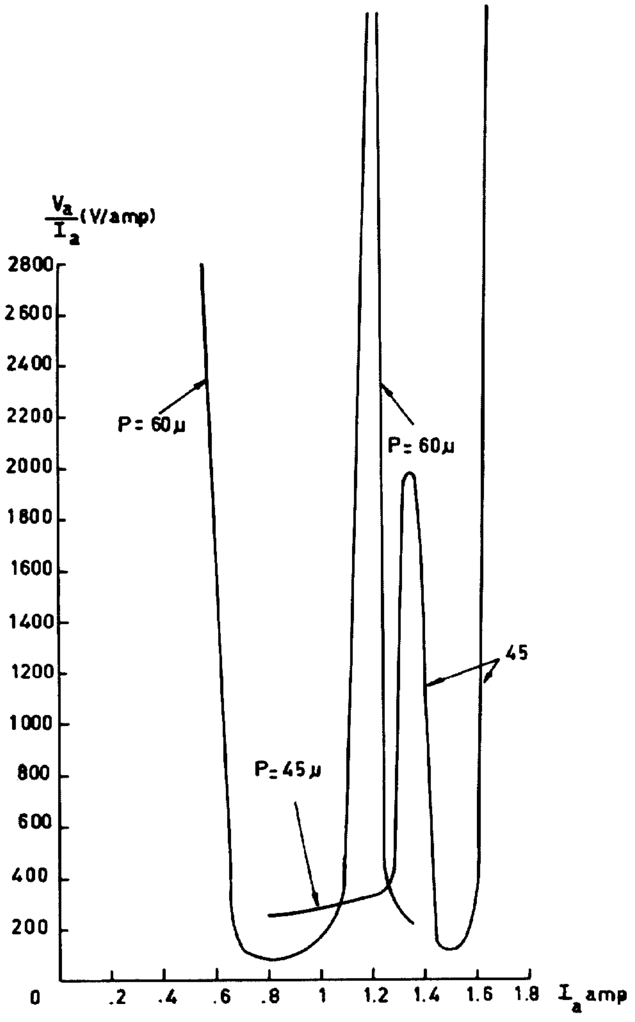


Fig. 6'. Impedance of the arc discharge deduced from Fig. 6.

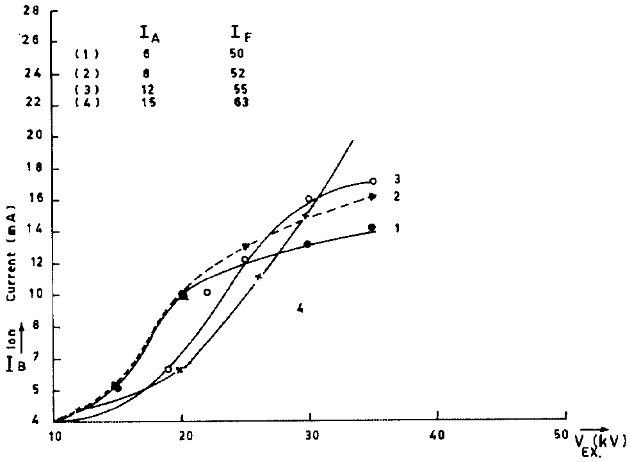


Fig. 7. Extraction characteristics at different arc currents, before electrode alignment.

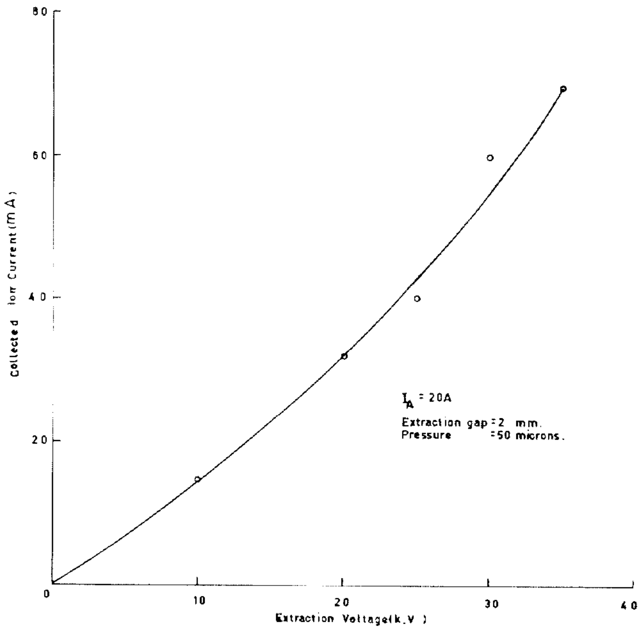


Fig. 8. Extraction characteristic after alignment of the electrodes.

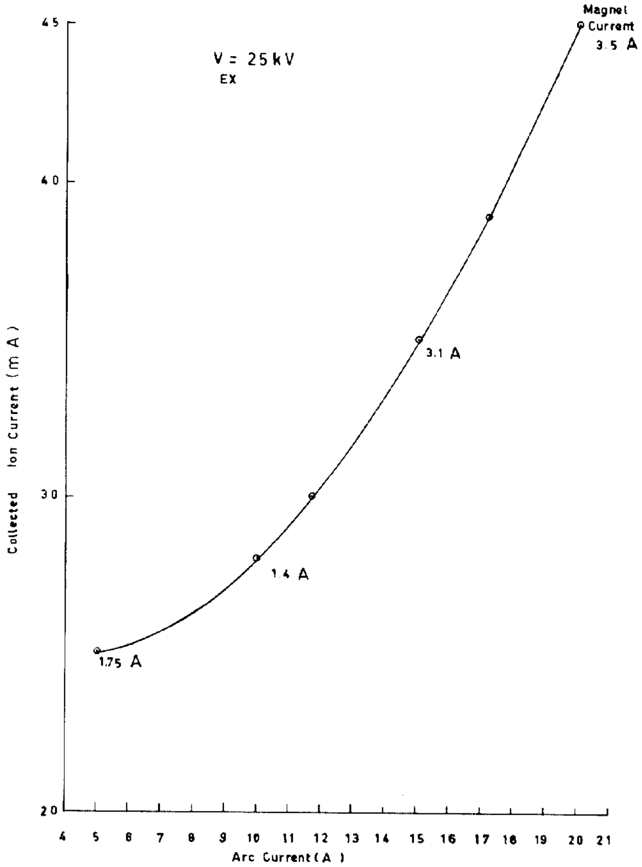


Fig. 9. The relation between the arc current and ion current.

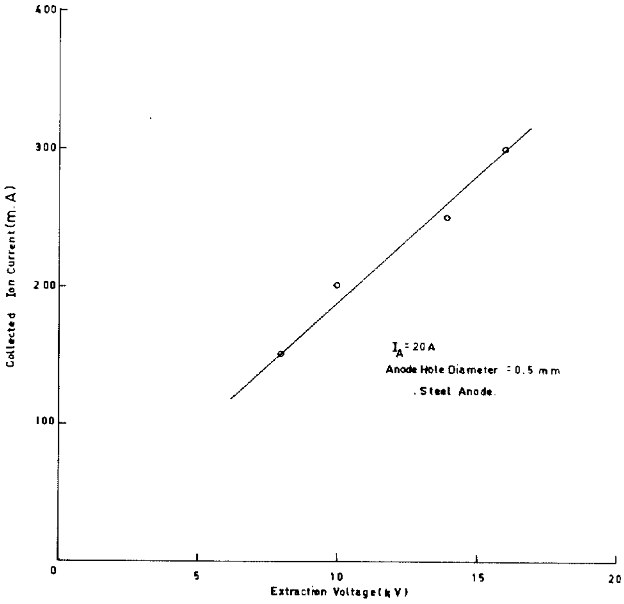


Fig. 10. Extraction characteristics using an expansion cup.