ION ENERGY CHARACTERISTICS OF A PENNING ION SOURCE

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ABSTRACT

Simultaneous measurements of the energy spectrum of the ion beam and the discharge and the total ion currents from a Penning ion source have been carried out under various operating conditions. The width of the energy spectrum increases to a maximum in the transition region between the low pressure mode and the high pressure mode and this is believed to be due to instabilities associated with the mode transition. The ionic composition has also been measured for various gases.

Keyword : Penning ion source, energy spectrum, ionic composition.

INTRODUCTION

The Penning type ion source has been very well described in the literature in view of its frequent use as a source of intense beams of multiply charged ions. In the Penning source, the electrons emitted by a cold cathode oscillate in an axial magnetic field and cause ionization by collision with the gas molecules. The ions can be extracted in the axial or radial direction with a suitable extracting system.

The discharge characteristics of the Penning type source have been investigated by many workers and reviewed in great detail by Hooper [1]. The discharge has many different modes of operation depending on various parameters like gas pressure, discharge voltage and the magnetic field, and the electronic and ionic densities in the discharge chamber vary with various modes of operation. It is expected that the energy spectum of the ion beam extracted from the source should also show variations with the source conditions. Earlier investigations on the energy spectrum of the ion beams in such sources indicate a strong dependence on anode voltage and the magnetic field [2, 3], but correlations between the variations in the energy spectra and the modes of operation of the discharge have not been available in the literature. In the present work, simultaneous measurements have been carried out on the energy spectra and the discharge and total ion currents from a Penning ion source in order to enable correlations between the energy distribution of the ions and the operating modes of the discharge.

The various modes of operation of the Penning discharge have been discussed by Schuurman [4]. At low pressures, the discharge operates in either of two modes depending on the magnetic field and these are called the low magnetic field (LMF) mode and the high magnetic field (HMF) mode. In both these modes, the ion density in the discharge is much smaller than the electron density because, while the electrons cannot rapidly cross the confining magnetic field to reach the anode, the ions fall freely to the cathodes along the magnetic field lines. In the LMF mode, there exists a cloud of negative charge spread out over the whole volume of the chamber. In the HMF mode, the potential on the axis drops to the value of the cathode potential and a field-free plasma region appears around the axis of the discharge. Schuurman's investigations pertain mostly to these two modes. At higher pressures the discharge enters an unstable transition mode in which the electron and ion densities become approximately equal throughout the volume of the discharge. Strong axial electric fields may exist in the central plasma since the particle mean free path is still much larger than the dimensions of the discharge. At still higher pressures, the discharge enters the high pressure (HP) mode in which, because of smaller mean free paths, the ion distribution gets thermalized and the voltage drop occurs in cathode sheaths. This region has not been easily amenable to theoretical investigations because of the many complex phenomena involved and the presence of strong beam-plasma oscillations.

EXPERIMENTAL

The source constructed for the investigations has a stainless steel cylinder of 20 mm length and 25 mm diameter as the anode, while the cathodes are made of cylindrical copper blocks of 6 mm length and 18 mm diameter and rigidly fixed to the anode cylinder at its two ends with rings of teflon in between for insulation. A 1 mm slot is provided in the anode for radial extraction of the ion beam. The entire assembly is mounted on a brass pillar which is fixed to the source flange through a threaded porcelain pillar. The gas is admitted directly into the discharge chamber through a glass capillary tube. The axial magnetic field is provided by an electromagnet capable of producing a field upto 2,000 gauss.

The energy spectrum of the ion beam is obtained by extracting the ions into an electrostatic analyzer of the cylindrical condenser type with 8 cm radius and 90° deflection angle. The potentials to the electrostatic analyzer plates are applied from a highly stabilized supply and the ion current at the exit of the electrostatic analyzer is measured by an electrometer. With a strong differential pumping between the source and the analyzer, the latter has been operated without deterioration in performance upto source pressures of about 10^{-3} Torr. The source could be fitted with a few modifications to a double focusing mass spectro meter of the Mattauch-Herzog geometry having a 10 cm radius electrostatic analyzer and a 10 cm mean radius magnetic analyzer. The mass spectrometer is provided with electrical detection and the mass spectra are obtained by magnetic scanning. This instrument has been used for the analysis of the composition of the ion beam for various feed gases in the source.

RESULTS AND DISCUSSION

In view of the fact that the boundaries between the various modes of the discharge are known only qualitatively, it was essential first to identify the various modes and mode transitions for the ion source used for the investigations. To achieve this, the total positive ion current extracted from the source was measured by a Faraday collector at the exit of the source slit, as a function of the discharge voltage, magnetic field and the gas pressure. Simultaneously the discharge current between the anode and the cathodes in the discharge chamber was also monitored. Figures 1 and 2 show the variations of the discharge and the total ion currents with the magnetic field and gas pressure respectively. The discharge and ion currents show similar variations indicating that any effect the field or pressure has on the discharge current is reflected atleast qualitatively on the ion current as well. It would thus be possible to identify the various modes of operation from the ion current characteristics in the same way as from the discharge current variations.

The dependence of discharge current on magnetic field shown in figure 1 is similar to that observed by Schuurman [4]. The region to the left of the current maximum is the LMF mode while that to the right corresponds to the HMF mode. The value of threshold magnetic field necessary to initiate the discharge could not be measured accurately but a discharge current in excess of 100 μA was obtained even at a field of 100 gauss.

The discharge and ion currents show interesting variations with gas pressure as shown in figure 2. The linear region at pressures below 10^{-4} Torr corresponds to the low pressure modes. At a presure of 2×10^{-4} Torr

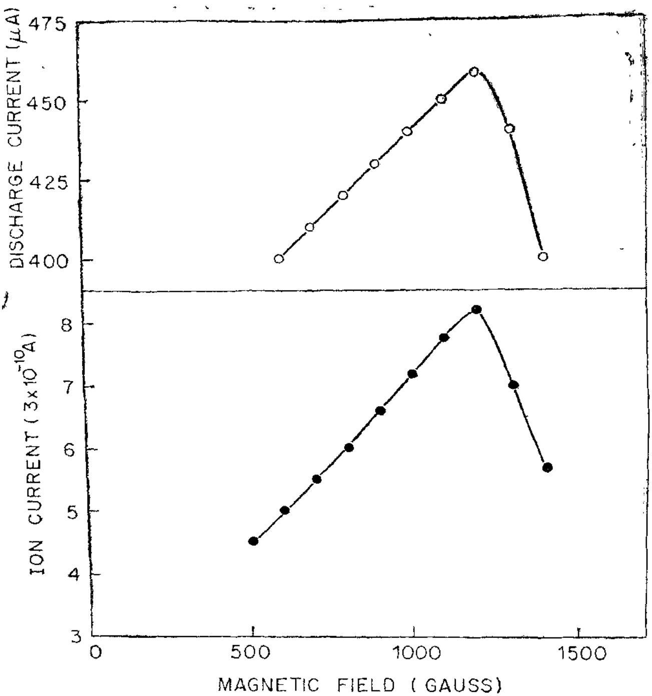

FIG. 1. Variation of discharge and ion currents with magnetic field; discharge voltage 2 kV, source pressure 5×10^{-5} Torr.

the ion current shows a drop to a sharp minimum but increases again with increasing pressure. The fall is due to the onset of the transition mode in which the plasma switches over to a quasineutral regime with the electron and ion densities being approximately equal in the discharge volume. This is followed by the transition to the high pressure mode. The range of the transition mode depends however on the values of the magnetic field and the discharge voltage. At very high magnetic fields the transition mode is not observed.

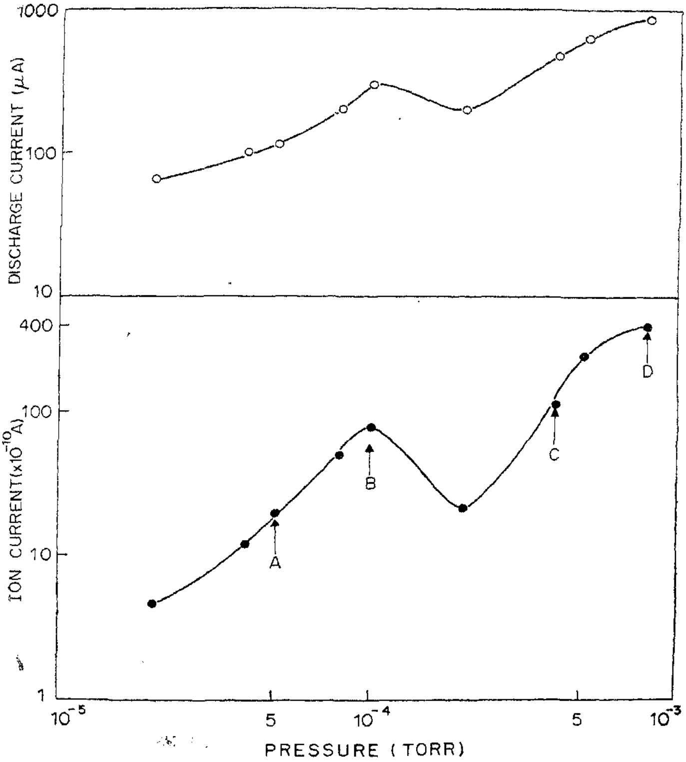

FIG. 2. Variation of discharge and ion currents with pressure; discharge voltage 2 kV, magnetic field 1000 gauss.

Having thus identified the various modes of operation, the energy spectrum of the ion beam was measured at various gas pressures, using the electrostatic analyzer. Figure 3 shows the energy spectra of the ion beam at different pressures. The corresponding points of operation of the discharge are marked on the pressure *vs* ion current curve in Fig. 2. The

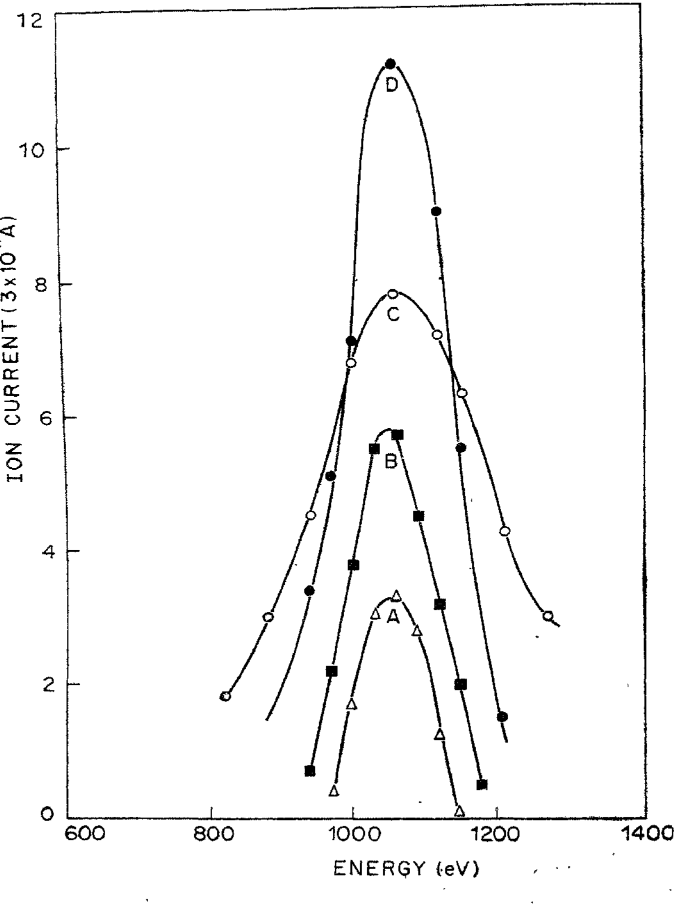

FIG. 3. Energy spectra of the ion beam at different pressures; discharge voltage 2 kV extractor voltage 1 kV.

spectra were obtained at a discharge voltage of 2000 V, an extractor voltage of 1000 V and a magnetic field of 1000 gauss. The energy spectrum is nearly symmetrical at low pressures. The full width at half maximum is about 120 eV and increases slightly with increasing pressure. At a pressure of 5·0 × 10^{-4} Torr however, the energy spectrum widens out abruptly; the full width being 350 eV. A predominant high energy tail is observed in the spectrum with ion energies reaching a value of upto 1600 eV. At higher pressures the width drops back to about 180 eV with the shape of the spectrum resembling that at the low pressure mode of operation. In Fig. 4, the width of the distribution is plotted against the gas pressure and the widening of the spectrum at about 5·0 × 10^{-4} Torr is clearly indicated.

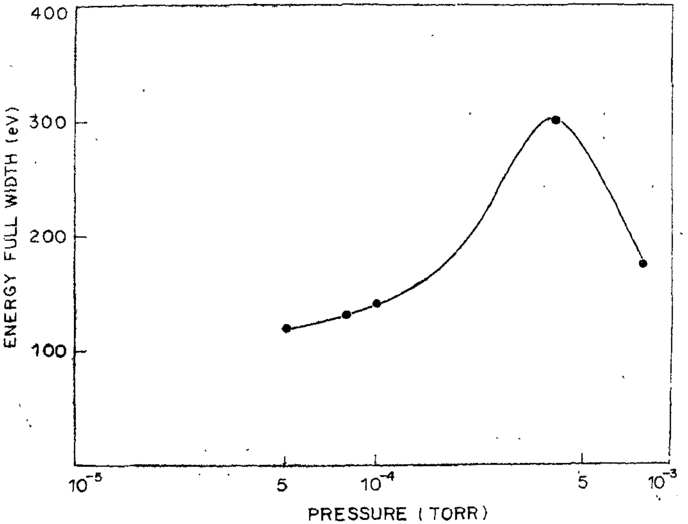

Fig. 4. Variation of the energy width with pressure; discharge voltage 2 kV, extractor voltage 1 kV.

The main result of the measurements is the abrupt widening of the energy spectrum which occurs at the onset of the transition mode. Hooper [1] has suggested the existence of strong electric fields in the plasma sufficient o accelerate the electrons to very high energies. Transfer of energy from the electrons to the positive ions is likely to occur through beam-plasma oscillations which have been observed by many workers [2, 3] along with the switching over of the discharge to the high pressure, high current mode of operation. It would appear reasonable to correlate the observed energy spread during the mode transition with the energy transfer through such instabilities in the plasma.

Hooper [1] has reviewed the work on plasma instabilities in the Penning discharge. The beam-plasma instability is believed to be the most prominent in the high pressure mode. Helmer and Jepsen [5] and Knauer [6] have observed that in the low pressure mode, the electron cloud rotates in the radial electric field and the axial magnetic field and have measured the frequency of rotation using a split-anode. This rotation is a form of the neutral-drag instability. In addition, the Penning discharge is also subject to the diocotron instability which arises in an unneutralized charge sheet of finite width in the presence of a magnetic field. This is a form of cross-field instability and is a result of interaction between two surface waves which travel in opposite directions along the two sheet surfaces. This instability has been examined in relation to the Penning discharge by Knauer [7] and Knauer and Poeschel (8). The instability criteria depend on the magnetic field, the length of the discharge and the anode sheath thickness. Using an approximate calculation, diocotron instability can be expected if $T \leq L/5B$ where, T is the anode sheath thickness in cm, L is the length of the discharge in cm and B is the magnetic field in kilogauss. For the present case, where $L = 1{\cdot}8$ cm and $B = 1$ kilogauss, this instability can be present if $T \leq 3{\cdot}6$ mm. Experimental investigations by Knauer and Poeschel [8] indicate that in the Penning discharge this instability actually occurs periodically because of the successive growth and shrinkage of the anode sheath.

The composition of the ion beam from the Penning source has been measured by many earlier investigators, particularly at high currents and in pulsed operations [2, 9–11]. The source produce an abundance of multiply charged ions and charge states of upto 10 for argon and 12 for xenon have been detected in various types of Penning sources [12]. We have measured the composition of the ion beam for argon, nitrogen, oxygen and carbon dioxide in the low pressure region and the results are shown in Table I. Our results for nitrogen and oxygen indicate a strong dissociation in the source and are in general agreement with earlier results. For example, Barnett *et al.* [10] as also Prelec and Isaila [13] have reported equal intensity for the atomic and molecular nitrogen ions in the beam. The amount of doubly

TABLE I

Ion beam composition for the Penning source

Gas	Ionic species	Relative intensity
Argon	A^{+}	100·0
	A^{+2}	21·2
Oxygen	O_2^{+}	100·0
	O^{+}	45·0
	O^{+2}	4·2
Nitrogen	N^{+}	100·0
	N^{2+}	63·0
	N^{2+}	5·6
Carbon dioxide	CO_2^{+}	100·0
	CO^{+}	40·2
	C^{+}	11·8

charged argon ions in argon has been low in our case, though it is interesting that Prelec and Isaila [13] and Baumann *et al.* [14] have also reported a lower intensity of A^{2+} ions than the A^{+} ions in the argon beam. The results indicate that the multiply charged ions become more abundant in the beam as the discharge is operated at higher currents. We have not been able to find much earlier data on carbon dioxide but our results conform to the tendency of strong dissociation of molecular gases in the Penning source.

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