A SOURCE FOR MULTIPLY-CHARGED IONS

G. S. Mavrogenes, W. J. Ramler, and C. B. Turner

Argonne National Laboratory
Argonne, Illinois

Summary

A hot cathode oscillatory discharge source was investigated for d.c. operation to determine the charge-state yield of ions for carbon, nitrogen, oxygen, neon and argon gases and to determine the parameters that effected these yields and source stability. Source principles and construction are similar to that reported by Morosov,[1] Papineau,[2] and Basile.[3]

As an adjunct to the design of a high power heavy ion cyclotron, investigations have been made of a d.c. hot cathode oscillatory discharge similar to the Morosov[1] ion source. Since other experimenters[2,3,4] have investigated only the nitrogen yield from d.c. operated units, it was the intent of these endeavors to establish the d.c. capabilities of this source to provide carbon, nitrogen, oxygen, neon and argon ions. The relative yields of multiply-charged ions were found to be critically dependent on minimal gas flow consistent with arc stability alignment of the cathodes with respect to the source aperture, arc current and voltage, and cathode material. Total yields were dependent on slit area and arc current. The location of the gas inlet to the discharge chamber was irrelevant. The introductions of heat shields reduced the cathode heater power to 300 watts.

Source Description

Figure 1 is a schematic of the source. The oscillating electrons and resultant plasma are established between the W cathodes K_1 (5/16 O.D. x 3/8 inch) and K_2 (5/16 inch O.D. x 3/4 inch). The arc chamber, C, is a water-cooled copper cylinder 4-3/4 inches long with an I.D. of 5/16 inch and an O.D. of 15/16 inch.

Cathode K_1 is indirectly heated by electron bombardment from an 0.070 inch dia. W filament F operated at a negative potential of 1 kV with respect to K_1. The cathode heat shields, HSH, reduced the required electron bombardment power from 1 kW to 300 W (1 kV and 0.3 A). Both cathodes, K_1 and K_2, are at the same potential and the current of K_2 is monitored during operation.

Gas flows into the source structure through the gas inlet and then into the distribution plenum (3/16 inch I.D.) which is attached to the anode C. From the plenum, the gas enters the arc chamber through ten 0.030 inch diameter holes spaced 1/4 inch apart. For test purposes, the anode is constructed so that the plenum can be removed from the anode and the distribution of the gas inlet holes can be modified.

The over-all height of the source is 7-1/2 inches.

Test Arrangement

A 12" circular magnet was used to provide the constraining field for the source discharge and in addition, it was used as a 180° spectrometer for the analysis of the ions emanating from the source.

The analyzing chamber, 65 x 25-1/2 x 7-1/2 inches high, was pumped by two oil diffusion pumps of 10 and 6 inch size. The base pressure without gas input was 1×10^{-6} Torr and about 5×10^{-6} Torr for source testing.

The ion source, extraction dee, collecting slit (Faraday cup) were located in the analyzing chamber. With the source at ground potential, the extracting dee and collecting slit were operated at a negative potential of 10 kV (0.1% regulated). The extracting slit was rectangular, 5 mm x 2 mm wide, and spaced 1/8 inch from the source. The movable Faraday cup was precisely calibrated for mechanical position and the collected current during a spectrum scan was recorded on a strip chart recorder.

Since the magnet size seriously limited the field homogenity throughout the analyzing region precise field plots were made and computer trajectory plots were obtained for ions for a z/A ratio of 1 to 0.05. These plots and ion calibration runs were then used to identify the z/A yield of the test source.

Gas Flow

The gas flow rate to the source is most important to establish the operation

of the source in respect to ion yield, evaluation of source performance and to establish the gas load on future accelerator's vacuum system. From these tests, it was determined that a gas flow stability of about 0.05 cc/min or better (.01 cc/min) is necessary to firmly establish the stability of the arc at a chosen point of operation.

Gas flow to the source was measured by a Hastings meter with a range of 0 to 10 cc/min. (STP). This instrument was precalibrated for the various type gases that were used. Meter accuracy was good (about 1%) and the instrument was quite dependable. The control of the flow rate was accomplished by using a needle valve.

Performance

Figure 2 sets forth the relative yield for various input gases when the source is operated at maximum d.c. power and minimum gas input. These values are the nominal yields obtained for day-to-day operation.

Figure 3 relates the ion output of the source (constant arc parameters) as a function of source aperture area; variation in area was accomplished by increasing the height of the aperture with the width dimensions being fixed. For this report, the source was operated with an aperture area of 7.5 mm^2 (5 mm x 1.5 mm) to give a total ion output of 20 mA. It is of interest to note that as the outside wall thickness (1/8 inch thick) of the aperture was decreased to about 1/16 inch at its edge and the outside was shaped (concave), the total ion output of the source increased and the focusing was greatly improved. The improvement is noted by comparing the dashed and solid curves. A further reduction in thickness to 1/32 inch and shaping increased the current to a level of 18 to 20 mA for an area of 7.5 mm^2. It was our tentative observation that the yield of high charge state ions increased with the thin wall aperture, but further data are necessary to firmly establish this conclusion.

Since the resolution and cooling of the analyzing system did not permit continuous operation and precise analysis at high extracted ion currents (50 mA), the relative yields of nitrogen ions were determined for total currents ranging from 5 mA to 30 mA. Variation in the output current was achieved by changing the size of the source aperture and varying the gas flow so that the arc parameters remained constant. Over this range, the relative ion yield was unchanged. From this endeavor, it was concluded that the yield data obtained for 20 mA (5 mm x 1.5 mm) would be representative of 50 mA operation obtained with an aperture size of 10 mm x 2.0 mm. The gas flow required for 20 mA of ions (7.5 mm^2) was 0.4 cc/min as compared to 0.7 cc/min for 50 mA performance (20 mm^2). The integrated spectrum current measured at the Faraday cup was 50 to 60% of the total reported ion yield. For these tests, no attempt was made to achieve a higher ratio of integrated to total current.

Nitrogen

A summation of the nitrogen endeavors are set forth by Figures 4 and 5 in which the relative charge state yields are given as a function of arc current and gas flow with an arc potential of 300 V.

The total yield and percentage of highly charged ions rose with arc current until about 7 A, at which point the total yield reached an approximate plateau, whereas the percentage of high charge states continued to increase up to the experimental limit of 10 A.

When the arc voltage was increased to 350 V, the N^{3+} yield increased by about 20%.

Stable arc operation was achieved for a gas flow as low as 0.4 cc/min. Below this value instability was experienced and data were not obtained. For a 1% stability in the yield of 4+ and 5+ ions, the variation in gas flow should not exceed about 0.01 cc/min.

Consistent N^{5+} yields of 0.15% were obtained with a gas flow of 0.4 cc/min, 10 A of arc current and 300 V. This yield decreased as the flow rate increased or as the arc current decreased; 0.1% for 9.5 A and 300 V.

Oxygen

Figure 6 illustrates the dependence of the relative yield of oxygen ions on arc current. These data were obtained with a gas flow of 1 cc/min. The spectrum is similar to that of nitrogen with a minor variation in respect to the 1+ and 2+ charge states. Again, the highest yield of multiple-charged ions was obtained when the gas flow approached the minimum flow for stable operation; arc potential was 300 V.

During the initial oxygen tests, the exit aperture of the source was graphite, but due to the sublimation of the graphite, the carbon ion content of the

total beam gradually increased (total current constant) until it was about the same level as the oxygen ions. When the carbon slit was replaced with tantalum, the carbon beam disappeared; the reported data were obtained with a Ta aperture.

Carbon

The source was tested with CO_2 gas and the percent relative yield of ^{12}C ions as a function of arc current is given by Figure 7. For 10 A of arc current and 300 V, the carbon ions were about 59% of the total ion yield. The oxygen reduces the percent yield of the carbon ions and is the difference between the summation of the quoted values for any operating point and 100%.

In general, arc stability was excellent and no deleterious carbon effects on the cathode were noted. Stable arc operation could be maintained at a gas flow rate as low as 0.8 cc/min.

Neon

Since the Ne gas was not isotopically pure, and the ^{20}Ne has higher ionization potentials and lower ionization cross sections than the above gases, the total ion yield can be expected to be less. As referenced to nitrogen operation, the total yield was 65% of the nitrogen current.

The data of Figure 8 were obtained for an arc current and voltage of 10 A and 300 V; stable operation was achieved with a gas flow of 0.7 cc/min.

Argon

Analysis of the $^{40}A^{+}$ ions could not be accomplished with the normal extraction voltage of 10 kV and the 8 kG magnetic field. To overcome this limitation, the extraction voltage was decreased to 7 kV and the magnetic field increased to 10 kG; all of the other argon ions were analyzed with the normal parameters.

The arc voltage was 300 V and the source was stably operated with a gas flow of 0.87 cc/min. Refer to Figure 2 for the yield argon ions.

Gas Input

The position of the gas inlet hole (1/16 inch I.D.) into the arc chamber was systematically varied along the length of the arc chamber without any significant change in source performance. In addition, a test was made using ten 0.030 inch diameter inlets spaced 0.25 inch apart and distributed along the length of the chamber. Even though there was no significant change in the performance of the source this arrangement was adopted as the method of gas distribution. These tests were only performed for nitrogen but we do not anticipate any change for the other gases.

Magnetic Field

The performance of the source was investigated for a magnetic field range of 10 to 5 kG. Essentially, the source was unaffected for this field range. Below 5 kG, the spectrometer was not capable of analysis but the arc operation was stable. In the region of 3 kG, a degree of arc voltage and current instability appeared. Below 3 kG, the arc was unstable and spark over occurred between the cathode K_2 and the anode (ground).

Arc Alignment

It was determined that the alignment of the arc axis with the magnetic field was quite critical for optimum high charge state yields. For example, one degree of misalignment (tilt) reduced the 3+ yield of the nitrogen arc by 25% with the lower ion charge states remaining about the same.

Cathode Materials

Cathode materials of tantalum, molybdenum, aluminum and tungsten were used and tungsten proved to be the best material in regard to total ion yield, arc stability, mechanical stability and over-all hours of operational life.

Cathode life (W) with respect to the different gases were:

Nitrogen	20 hours	10 Amperes-300 Volts
Neon	15 hours	10 Amperes-300 Volts
Argon	5 hours	10 Amperes-300 Volts

The life of the source was limited by the cathode erosion rate. The evaporated cathode material deposited at the water-cooled entrance to the arc chamber and if not carefully cleaned prior to a test run, this material would flake and short the cathode structure K_2 to ground. One anode was used throughout these tests of many hundreds of hours without any signs of erosion.

Comments

In the general analysis of these data, we can conclude that the greater the discharge current for a given voltage, the higher the yield of the higher ionization states. However, it is repeatedly

observed that for discharges of the same power and gas flow, the correspondence of composition was poor.[5] For example, a N discharge with a current of 10 A and 270 V was inferior to the same type discharge with an arc current of 9 A and 300 V. Even though the stepwise ionization process predominates in the production of multiple-charge states, the arc voltage is still an important factor and should be as high as possible.

The capabilities of this source have not been exhausted and numerous things remain to be done to further improve the high charge state yield.

For the proposed ANL cyclotron, the discharge chamber geometry can be improved to increase the resistance of the arc and thereby achieve a higher voltage drop. We are confident that a higher operating voltage will further enhance the yield of multiply-charged ions. In addition, an increase in the size of the source will upgrade the power capabilities of the source. At present, operation of the 3 kW power level is marginal. For further source improvements, it would be profitable to continue the investigation of aperture wall thickness and the relative alignment of the cathodes and the aperture wall.

We have not attempted to study the emittance characteristic of the source or to obtain a high percentage of integrated current at a 1/2 turn distance. The latter will require a further investigation of the extraction system and most likely will require further improvement in the homogeneity of the spectrometer's magnetic field.

Without a doubt, the described source will be quite useful for internal cyclotron operation to achieve low states of ionization for the heavy mass projectiles in addition to providing ions of high charge states, such as, 4+ carbon, 5+ nitrogen, 5+ oxygen, 4+ neon and 8+ argon. Based upon these investigations, it is our opinion that for projectiles of still higher z/A ratios, one will have to resort to external type sources, velocity stripping techniques or possibly fission type sources.

References

[1] Morosov, P. N., Makov, B. M., and Joffe, M. S., Atomaya Energiya, 3, 272 (1957).

[2] Papineau, A., Benezech, P., and Maillard, R., J. Physique Radium, 21, 410 (1960).

[3] Basile, R. and Lagrange, J. M., J. Physique Radium 23, 111A (1962).

[4] Jones, R. J. and Zucker, A., R.S.I. 25, No. 6, 562 (1954).

[5] Pigarov, Y. and Morosov, P., Soviet Physics, Technical Physics, 6, No. 4, 342 (1961).

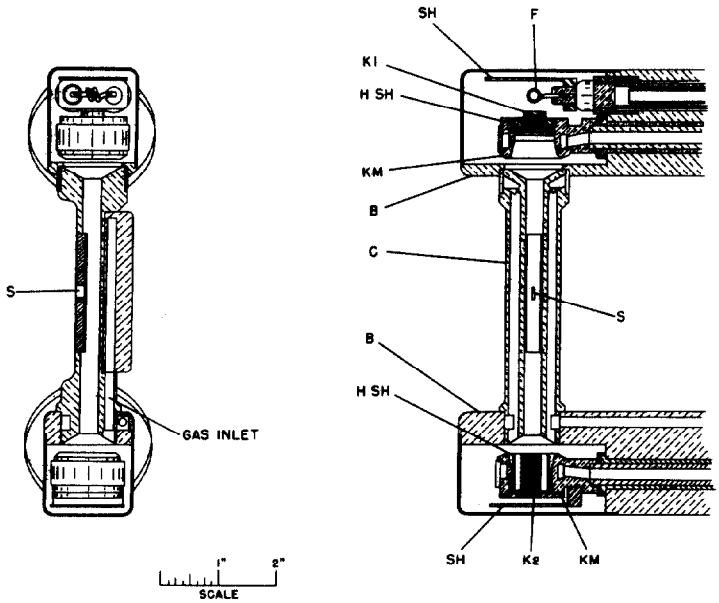

Fig. 1. Ion Source Schematic.
K_1 - Hot Cathode (W); K_2 - Reflector Cathode (W)
KM - Cathode Mount - Copper and Water Cooled
SH - Electron Shield (W)
H SH - Cathode Heat Shields
S - Source Aperture
C - Copper Anode.

OPTIMUM YIELDS FOR VARIOUS GASES
(The percentage being that of the total ion current analyzed)

	1^+	2^+	3^+	4^+	5^+	6^+	7^+	8^+	Σ
^{14}N	22%	42%	31.2%	4.2%	0.15%	-	-	-	50 mA
^{16}O	37.8	37.8	21	3.2	0.05	-	-	-	40 mA
*^{12}C	12	27.8	16.4	1.2	-	-	-	-	40 mA
^{20}Ne	30	41	23	2.1	-	-	-	-	35 mA
^{40}A	8.7	25	42.6	18.5	3.3	1	0.6	0.2	40 mA

*CO_2 gas.

Fig. 2. Relative ion yields for various gases (arc voltage 300 V, arc current 10 10 A).

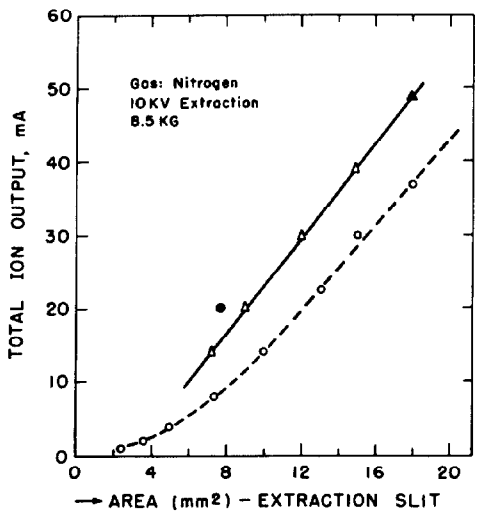

Fig. 3. Total ion output (mA) vs aperture slit area (mm^2). Dashed curve - 1/8 inch thick aperture wall; solid curve - 1/16 inch thick aperture wall; one point - 1/32, 20 mA 7.5 mm^2. (Nitrogen gas, arc of 300 V - 10 A).

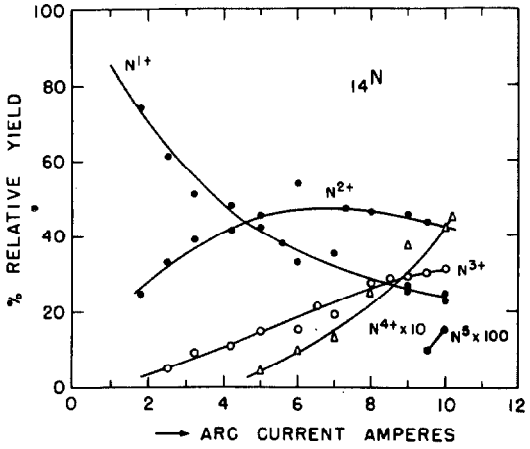

Fig. 4. ^{14}N - % Relative Yield vs Arc Current. (Arc voltage 300 V, gas flow 0.4 cc, aperture slit 7.5 mm^2).

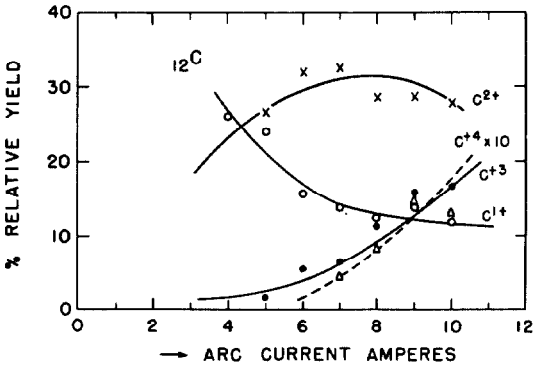

Fig. 7. ^{12}C - % Relative yield vs arc durrent. (Gas CO_2, flow 0.6 cc/min, arc voltage 300V, aperture slit 7.5 mm^2).

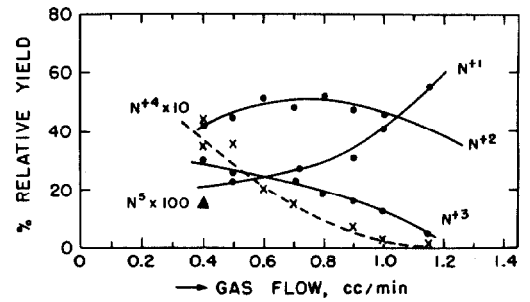

Fig. 5. N_{14} - % Relative yield vs gas flow rate. (Arc voltage 300V - 10A, aperture slit 7.5mm^2).

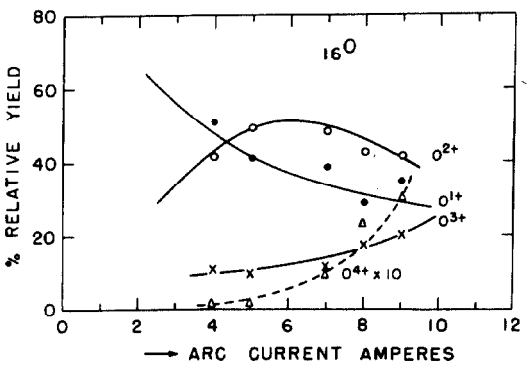

Fig. 6. 160 - % Relative yield vs arc current. (Arc voltage 300V, gas flow 1 cc/min, aperture slit 7.5 mm^2).

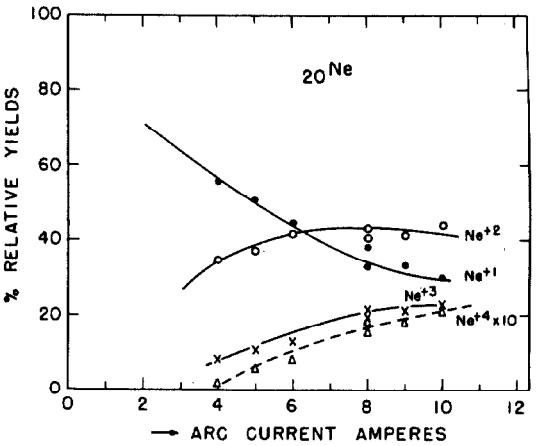

Fig. 8. ^{20}Ne - % Relative yield vs arc current (Gas flow 0.7 cc/min, arc voltage 300V, aperture slit 7.5 mm^2).