INITIAL EXPERIENCE IN ION PRODUCTION USING AN ULTRA-HIGH POWER DENSITY METHOD *

T.Y.T. Kuo and J. S. Laughlin

Division of Biophysics, Sloan-Kettering Institute, New York, N. Y. USA

Abstract

A mechanism to adjust the cross-section of the arc column of a cold cathode P.I.G. ion source has been developed. The cross-section of the plasma column, and therefore the electron flux density can be adjusted over a wide range with a fixed ion source power. We have achieved in producing an arc column with power density up to about 370 kW/cm^2 and about 140 kW/cm^3. With this ultra-high power density, a great improvement on ion production has been obtained. The peak beam currents of the doubly charged He-3 and He-4 have been increased, from 150 µA to 750 µA and from 50 µA to 400 µA respectively, using our compact cyclotron. **

Introduction

Ion-heated cold cathode P.I.G. ion sources with side extraction for the production of heavy ions have been investigated by many authors(1-16). Comprehensive tabulations listing the performance figures and references for a large number of P.I.G. sources have been given in the review articles by Bennett(17-19) and Osher(20). Most of the reported data were resulted from test facilities and expressed in terms of current intensity and of the percentage of each charge state for a given particle. The characteristics of these sources were described in terms of design features and the interdependence of their operating parameters, such as arc voltage, arc current, arc power, gas flow, tank pressure, cathode and anode geometry, cathode materials and lifetime, extracting voltage, magnet field effect and so on.

In this paper we report some initial experience with a PIG source‡in which the cross section of the plasma column is adjustable. The study was done using our CS-15 compact cyclotron by measuring internal beam currents at extraction radius and extracted beam currents on external target. While the arc voltage and current, therefore arc power, are maintained constant, arc power density or electron flux density can be regarded as a new parameter. Ion production is found not only dependent on arc power input but also strongly on power density used. Of course adjusting arc power already implies that power density is increased or decreased. We wish to point out that after the maximum arc power is reached, it is still possible to increase the power density by tighting up the cross section of arc column.

Method and Operation

The geometric arrangement of the ion source anode between the puller and the shield is illustrated in Fig. 1. The anode bore is 6.3 mm and is aligned with a hole of the same size at the bottom housing of the cathode. The hole in the upper cathode housong is only 3.0 mm in diameter. The cathodes are made of tantalum; 3 mm thick by 8 mm wide. The cathode stem is 1.2 mm by 3 mm, a cross section giving a balanced heat conduction rate and cathode temperature for He-3 ion production.

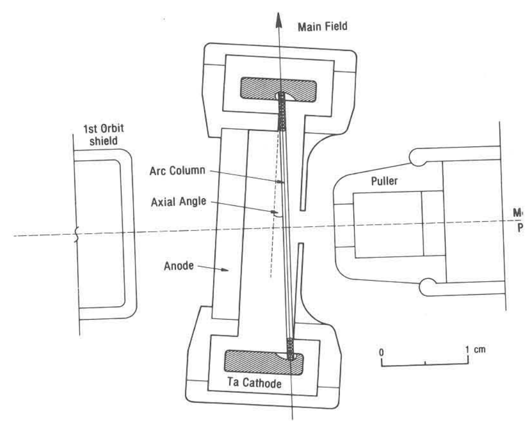

Fig. 1. The structure of the ion source head, axial rotation is about 5.5 degrees.

The ion source is adjustable in four independent coordinates, namely, the horizontal (puller anode gap), the radial (ion entrance angle to puller slit), the vertical (alignment of extraction slit with median plane) and finally the axial rotation control. The axial angle control rotates the ion source head so that the opposite edges of the upper and lower anode openings are used to limit the size of the arc column. In Fig. 1, the rotation is about 5.5 degrees and the cross section is about 0.27 mm^2. Unfortunately this rotation causes the arc column to retreat away from the extraction slit in either direction of rotation. The slit surface also becomes oblique with respect to the puller. So the axial rotation actually produces the combined effect of increased arc power density and some undesirable conditions. To remedy this difficulty, the anode was bored with an angle of approximately 6 degrees from both ends as shown in Fig. 2. Here the ion plasma column is close to the extraction slit at any operating angle. The improvement in beam currents over that from Fig. 1 will be shown in Fig. 6.

The computed arc column cross-section area and the relative power density at a given angle, as used in our setup, is plotted in Fig. 3. If the arc power at high thermionic mode is about 1 kW and is maintained constant for all angles, one obtains

Proc. 7th Int. Conf. on Cyclotrons and their Applications (Birkhäuser, Basel, 1975), p. 381-385

the following table:

Axial Angle	Arc Column C-S (mm^2)	Power Density kW/cm^2	Power Density kW/cm^3
0°	6.5	15.5	6.0
1°	5.0	20.1	7.8
2°	3.8	29.4	11.4
3°	2.5	40.5	15.6
4°	1.4	57.4	22.2
5°	0.5	155.0	78.0
5.5°	0.27	372.0	144.0

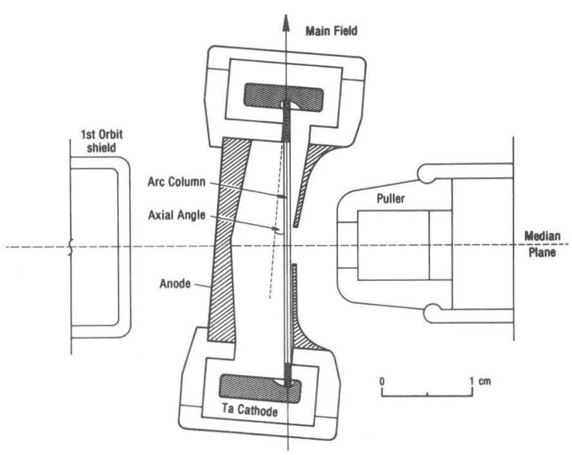

Fig. 2. Cross section of the anode configuration with 6 deg. tapered bore.

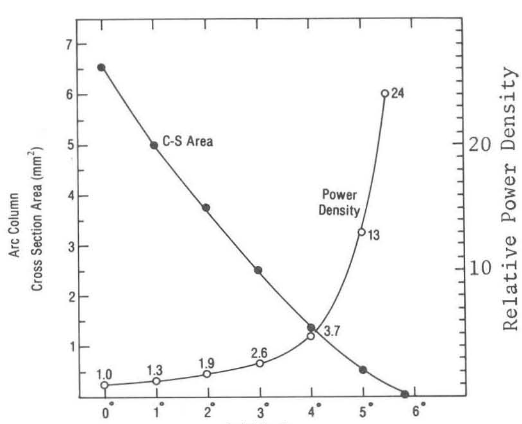

Fig. 3. The arc column cross-section area and relative power density as a function of axial angle.

Typically the ion source is operated in three arc power stages:

Mode	Arc Voltage	Arc Current
Penning	200-2500 V	0.001-100 mA
Low Thermionic	600-1000 V	300-500 mA
High Thermionic	200- 300 V	3.5-5.0 A

The thermionic modes can only be struck at certain axial angle where the projection area on cathode, available for emission of electrons due to bombardment of positive ions, is large enough. Once the arc is started, the source head can be rotated to obtain desired arc conditions. For the Penning mode, the arc current shows a step function type of dependence on the axial angle. The angular position at which the arc extinguishes is, in turn, dependent on the gas flow and arc voltage used. Increasing gas flow and arc voltage will allow the arc to survive at larger angle,i.e., smaller arc column cross section.

The typical pattern of erosion by spluttering is indicated in Fig. 1 where the axial angle is about 5.5 degrees. A pair of cathodes can be used twice by exchanging the upper with the lower cathode. Total lifetime is about 100 hours.

Results

Axial angle and arc power dependence

Fig. 4 and 5 summarize the relative internal beam currents of four types of particles plotted against the angle of axial rotation of the ion source. The beam currents were measured at the extraction radius of the cyclotron. The dependence on axial angle at three typical arc power stages is shown for each particle. Each curve was obtained at a fixed rf dee voltage. The relative scale is used only to compare the beam current at a given arc power mode.

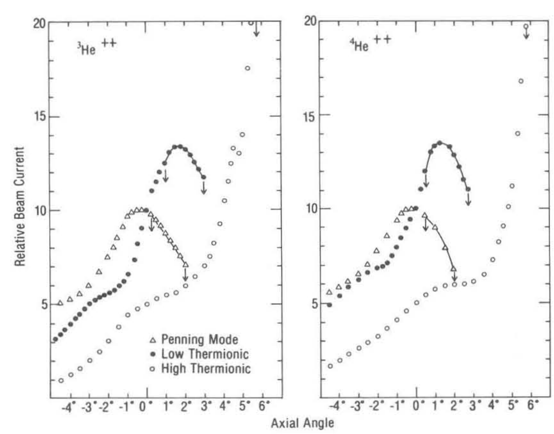

Fig. 4. Relative $^3He^{++}$ and $^4He^{++}$ beam current as a function of axial angle, relative scale applies to individual curve only.

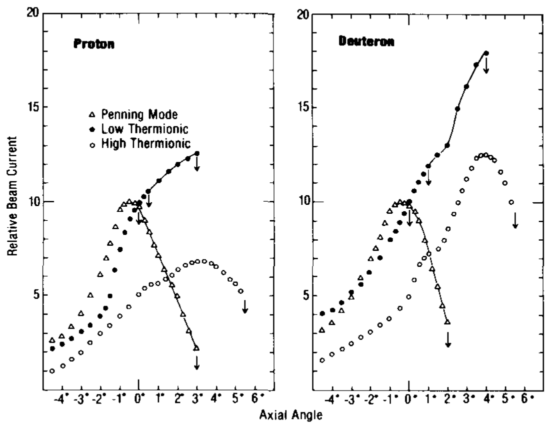

Fig. 5. Relative protons and deuterons beam current as a function of axial rotation, relative scale applies to individual curve only.

As mentioned in the last section that the effect of axial rotation represented the combined effects of the change of arc power density and the change of electro-geometric conditions; the behavior of beam current does not correspond directly to the behavior of ion production. When the rotation is counter clockwise, beam current always falls off for all cases. While there is little change in power density because the bottom hole is bigger and offset, the effect seemed to be due to the fact that the arc column moves away from the extraction slit.

When the Penning mode is used, beam currents peak around zero degree for all four particles. On the clockwise side, the beam current would suddenly drop to zero as indicated by a downward arrow where the arc extinguishes. More gas flow and higher arc potential can extend the arc existance at larger angle but the beam currents decrease monotonically, as shown by the data points linked by a solid line. This decrease of beam current may be related to the energy distribution of the emitted electrons at a given set of arc voltage and current and to the strength of magnetic field. As the cross section decreases, electrons with higher energy would not be confined in the arc column to oscillate between upper and lower cathodes thus lose their contribution in the ion production process. Another reason is the retractation of arc column from extraction slit. The Penning mode beam current is continuously adjustable at a given fixed dee voltage by adjusting arc voltage, gas flow and axial angle. The range of beam current depends strongly on the type of particle. For protons and deuterons, from a few picoamperes to a few hundred microamperes can be obtained. For $^3He^{++}$ and $^4He^{++}$, the peak is just a few microamperes.

When the low thermionic arc is used, the beam current continues to increase as the ion source is rotated clockwise. Further rotation would turn the arc into Penning mode or zero arc current stage. Again, increasing gas flow will allow the arc to exist at a larger axial angle but the maximum cutoff angle is about 3 degrees. The improvement of beam current using low thermionic arc was small, only 20 to 30 percent over the normal output at zero degree, probably because the loss due to the walkaway of ion column from the extraction slit is large as evidenced in the He beams. On the other hand, the variation of beam current level per unit change of axial angle is quite large. For a non-rotational source, a small misalignment of the anode would give rise to an appreciable fluctuation in beam current output between servicings of the ion source. The rotational method is able to compensate this error.

For the high thermionic mode operation with arc power at 1 kW, quite a different characteristic is seen. Here the beam currents of protons and deuterons peak around 4 degrees, very similar to those of He^{+2} beams at low thermionic stage. It seems that ion production at these conditions has reached saturation and the retreat of acr column from extraction slit decreases the effectiveness of ion extraction as axial angle is rotated further. For $^3He^{+2}$ and $^4He^{+2}$, the beam currents increase moderately from 0 degree (6 kW/cm^3) to 3 degrees (15.6 kW/cm^3), but very rapidly from 3 degrees to 5.5 degrees (144 kW/cm^3). A remarkable improvement of beam current over 300% is obtained. The increase of ion production must be even higher because the retractation of ion column must be taken into account.

To look at this effect, an anode configuration as shown in Fig. 2 was used. Fig. 6 illustrates the performance of the 23 MeV $^3He^{+2}$ internal beams as a function of rf dee voltage with 3 different arc conditions:

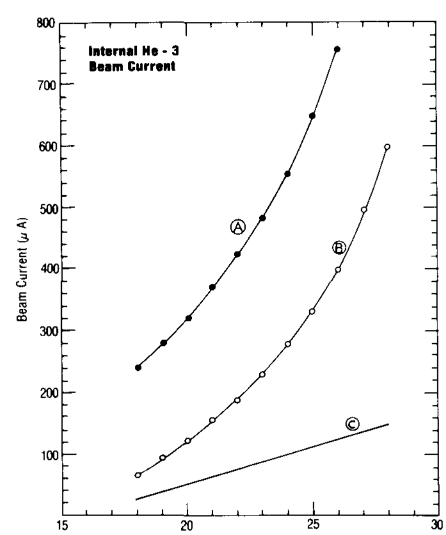

Fig. 6 $^3He^{+2}$ beam currents as a function of rf dee voltage.

Curve	Arc Power	Power Density
A (Fig.2)	1 kW	144 kW/cm^3
B (Fig.1)	1 kW	144 kW/cm^3
C	1 kW	6 kW/cm^3

Curve 'C' is the maximum output when non-rotational unit was used in the past. Curve 'B' is the routinely available beam current using configuration of Fig.1. As a comparison, curve 'A' represents the beam output achieved when configuration of Fig. 2 is utilized. At 18 kV (rf), beam output at condition A triples that at condition B and shows an order of magnitude increase over that at condition C. At 26 kV, the improvement from C to A is about 500%. This is because the rf power transmitted to beam power is already up to its limit. Also the extracted He ions which are outside of the rf phase width would load the central region down giving rise a problem of overheating.

Gas flow and power density interdependence

We have observed some differences in gas flow dependence characteristics between different gases when high arc power and high arc power density is used. There is a very slight improvement for protons and deuterons. For doubly charged ^{3}He and ^{4}He, however, the improvement is significant. This is shown in Fig. 7 for ^{3}He case. At a gas flow of about 3 c.c./min., the beam current does not show much increase before 3 degrees, then gains about 200% from 3 to 5 degrees. At a gas flow of 2 cc/min the rate of beam current increase due to power density change is much stronger. The total improvement is up to 600%.

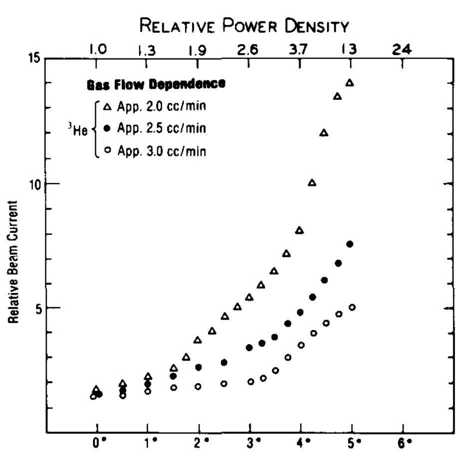

Fig. 7. Relative beam current output as a function of gas flow and arc power density. Data were obtained with high thermionic mode: 200 V, 5 A.

Another way to look at this dependence is to examine the ion output vs. gas flow at a given arc power density. Fig. 7 shows that at low power density of 6 kW/cm^3, the gas flow is not an important parameter. However, at high power density of 144 kW/cm^3, the beam current is a rapid function of the gas flow used. For the yield of highly charged heavy ions, similar results have been pointed out by Bennett(19, data of Pasyuk), Mallory(6), Kohno (15) and Miyazawa(14).

Discussion

The results we obtained here showed that higher ion production can be achieved by increasing the arc power density without adding more total arc power provided that the ion source is operated at certain power level. For the four types of particles which can be accelerated with our compact cyclotron, the improvement is only slight for protons, about 150% for deuterons, but 400% for $^3He^{++}$ and 600 % for $^4He^{++}$. The axial rotation method we used is very much structure dependent. By using the three power stages of the ion source controls and the rotational technique, the beam currents can be continuously adjusted over a wide range at a fixed dee voltage. Thus one obtains both the advantage of high current output of a P.I.G. source and the controllability of small output of a filament source. In addition, the problem of critical alignment of ion source is resolved.

The reason as to why our high current arc (5A) can exist in an extremely small ion column is that at low emission potential (200 V) and strong magnetic field (16 kG), the diameter of the helical path of the oscillating electrons will be very small, about 0.5 mm. These helical electron paths are initially evenly distributed over the cross section of the anode chamber. As the ion column is tighten up by mechanical means, the electrons emitted at that instant crowd into each other forming a column of electrons with very closely overlapped helical paths. Microscopic examination on a lightly burned cathode indicated that there was a small hill at the center of the burn spot and the erosion was a ring with outside diameter of just about 0.5 mm.

The fact that ion yield probability increases as arc power is increased has been a common observation. However, arc power density has not been selected as a distinctive ion source parameter. Evidence of this report shows that ion yield can be increased with higher power density even if the total arc power is reduced. Whether this scheme would help improve the ratio of high charged to low charged states is of interest and is yet to be explored.

Acknowledgement

The authors wish to thank Mr. R. Lee for his help in building the angle control and his assistance in the maintenance and operation of the cyclotron. Thanks also go to Prof. Blosser of Michigan State University and Dr. Mallory of Oak Ridge National Laboratory for helpful suggestions.

References

1. R. J. Jones and A. Zucker, Rev. Sci. Instr. 25, 562 (1954).
2. C.E. Anderson and K.W. Ehler, Rev. Sci. Instr. 27, 809 (1956).
3. J.R.J. Bennett, Proc. 5th Int. Cyclotron Conf., 499 (1969).
4. J.R.J. Bennett and B. Gavin, Particle Accelerator Vol.3, 85 (1972).
5. E.D. Hudson, M.L. Mallory and S.W. Mosko, IEEE Trans. Nucl. Sci. NS-18, No.3, 113 (1971).
6. M.L. Mallory, E.D. Hudson and G. Fuchs, IEEE Trans. Nucl. Sci. NS-19, No.2, 118 (1972).
7. D.J. Clark, et al, IEEE Trans. Nucl. Sci. NS-18, No.3, 102 (1971).
8. D.J. Clark, et al, Proc. 6th Int. Cyclo. Conf., 265 (1972).
9. H.A. Grunder, et al, IEEE Trans. Nucl. Sci. NS-19, No.2, 208 (1972).
10. B.F. Gavin, LBL-1219 (1972).
11. W.A. McFarlin, et al, IEEE Trans. Nucl. Sci. NS-18, No.3, 132 (1971).
12. R.A. Kenefick, et al, Proc. 6th Int. Cyclo. Conf. 258 (1972).
13. I. Kohno, et al, Proc. 5th Int. Cyclo. Conf., 487 (1969).
14. Y. Miyazawa, et al, IEEE Trans. Nucl. Sci. NS-18, No.2, 105 (1972).
15. I. Kohno, et al, IEEE Trans. Nucl. Sci. NS-18, No.2, 109 (1972).
16. E. Heinicke and H. Baumann, Nucl. Instr. Meth. 74, 229 (1969).
17. J.R.J. Bennett, Proc. 5th Int. Cyclo. Conf., 472 (1969).
18. J.R.J. Bennett, IEEE Trans. Nucl. Sci. NS-18, No.3, 55 (1971).
19. J.R.J. Bennett, IEEE Trans. Nucl. Sci. NS-19, No.2, 48 (1972).
20. J.E. osher, IEEE Trans. Nucl. Sci. NS-22, No.3, 1626 (1975).

* Supported in part by AEC(11-1)-3521 and NCI 08748-08B.

** The first prototype built by the Cyclotron Corporation, Berkeley, Calif. USA.

A.A. Fleischer, et al, " Design and perfeormance of a compact multi-particle cyclotron". Proc. 5th Int. Cyclo. Conf., 573 (1969).

‡ Built by the Cyclotron Corporation.

D.K. Wells, IEEE Trans. Nucl. Sci. NS-14, No.3, 70 (1967).

DISCUSSION

J.A. MARTIN: I would like to comment that at Oak Ridge we have noticed a similar effect for multiple-charged heavy ions. We find the angle of rotation of the ion source is very critical and the best angle is not zero. M. Mallory and E.D. Hudson have made these observations.

T.Y.T. KUO: This is correct. Two weeks ago, Dr. Mallory wrote to me about this phenomenon. By examining the structure of the ion source you refer to, I think there is some difference between your method and our method.

A. SCHMIDT: What changes in the characteristics of your arc discharge did you observe at high bending angles?

T.Y.T. KUO: Not very much. There is some change in arc voltage and arc current during the rotation, but they are about the same. The total power is more or less constant. But the effect of gas flow rate is large.

G. RYCKENWAERT: Could you give some comments on cathode lifetime compared to your previous source?

T.Y.T. KUO: We detected very little difference because the total power is the same. Average lifetime is about 100 hours.

C. BIETH: It seems to me that in this experiment you have mixed two phenomena: plasma movement in respect to the extraction slit and change in the arc density. Have you tried to move the extraction slit inside the plasma to look what happens on the extracted current?

T.Y.T. KUO: Yes, we have, as indicated in the text.

N.N. KRASNOV: Is your ion source operating under pulse regime or continuously? And what is the full arc power introduced in discharge?

T.Y.T. KUO: It is operated continuously. The arc power is about 1.2 kW.

N.N. KRASNOV: What is the effect of contamination by other gases, for example air, on the yield of doubly charged He ions?

T.Y.T. KUO: We use liquid nitrogen.

N.N. KRASNOV: Does your ion source disturb the motion of the beam at first turn because of axial angle?

T.Y.T. KUO: I believe there is some effect, particularly if the beam current is high. The central region is heavily loaded and overheating results from this.