IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

On the Ion Source and the Internal Beam Currents of the CS-15 Compact Cyclotron

T.Y.T. Kuo, R. Lee and J.S. Laughlin

Division of Biophysics
Sloan-Kettering Institute for Cancer Research

Introduction

The Sloan-Kettering Institute CS-15 compact cyclotron was the first prototype built by the Cyclotron Corporation in 1967. The ion source is a cold cathode P.I.G. type radially fitted into the 4-inch magnet gap. A description of the structure and operating characteristics of this source has been reported by Wells (1). Our experience with this ion source is that it is simple, small and capable of delivering large currents. However, we have had some difficulties in operating our cyclotron due to certain problems related to the ion source. For example, the beam current showed large fluctuations from time to time resulting in unpredictable cyclotron performance. The ion source was operated with limited configurations and beam current could only be adjusted by changing RF dee voltage. The search for the hidden parameters which govern the performance of the ion source was initiated. We discovered that the power density of the arc column plays an extremely important role, and it is, in fact, the hidden parameter we looked for.

Method and Operation

The geometric arrangement of the ion source anode between the puller and 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 housing 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 ^{3}He ion production.

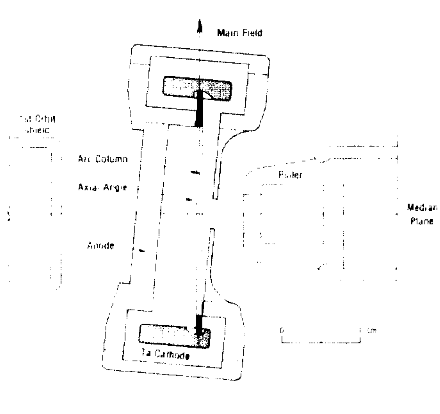


Fig. 1. Cross-Section of the ion source head.

The ion source is adjustable in four independent coordinates, namely, the horizontal, the radial, the vertical movements and the axial angle rotation. A photograph of these motor-driven mechanisms is shown in Fig. 2. The three linear controls are used to find the best initial orbit condition. The axial angle control rotates the ion source head to adjust the cross-section of the plasma column, and therefore the power density of the arc. Unfortunately this rotation causes the arc column to retreat away from the extraction slit in either direction of rotation. The anode 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 geometrical conditions.

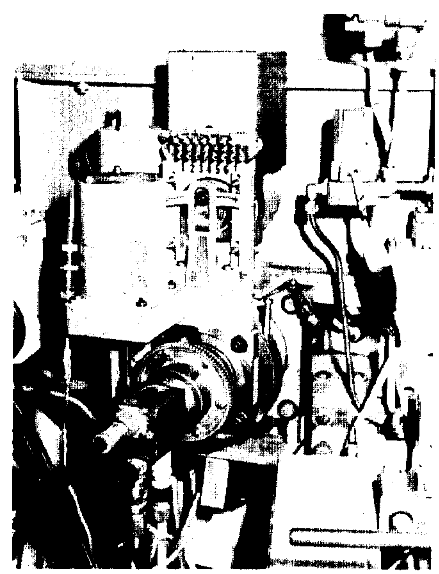


Fig. 2. The view of ion source position controls.

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

	Arc Voltage	Arc Current
Penning Mode	200-2000 V	0.001-100 mA
Low Thermionic	600-1000 V	300-500 mA
High Thermionic	200-300 V	3.3-5 A

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 the following table:

Axial Angle	Power Density KW/cm^2
0°	15.5
1°	20.1
2°	29.4
3°	40.5
4°	57.4
5°	155.0
5.5°	372.0

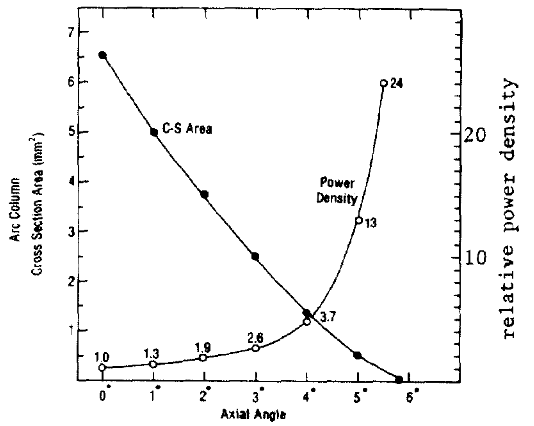


Fig.3. The arc column cross-section area and relative power density-as a function of axial angle

The typical pattern of burning off cathode material is indicated in Fig. 1 where the axial angle is about 5°. A pair of cathodes can be used twice by exchanging the upper with the lower cathode. Life time is about 100 hours even if a high power density is used.

Results

Axial angle and arc power dependence

Fig. 4 and Fig. 5 summarize the relative internal beam current of four types of particles plotted against the angle of axial rotation of the ion source. 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 within a given arc power mode. As mentioned in the last section that the effect of axial rotation represented the combined effect 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.

A general phenomenon can be seen, that is, when the rotation is counter clockwise beam current always falls off for all cases. While there is little change in power density, the effect seems to be solely due

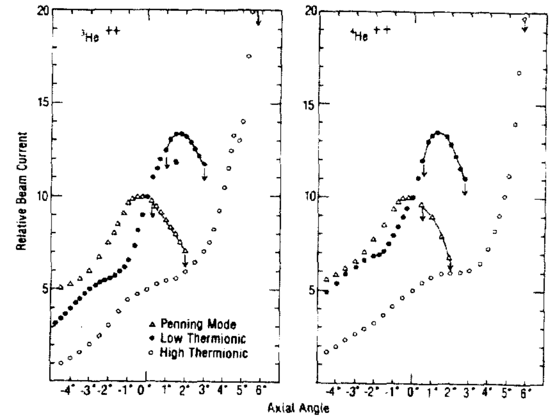


Fig. 4. Relative $^3He^{++}$ and $^4He^{++}$ beam current as a function of axial angle.

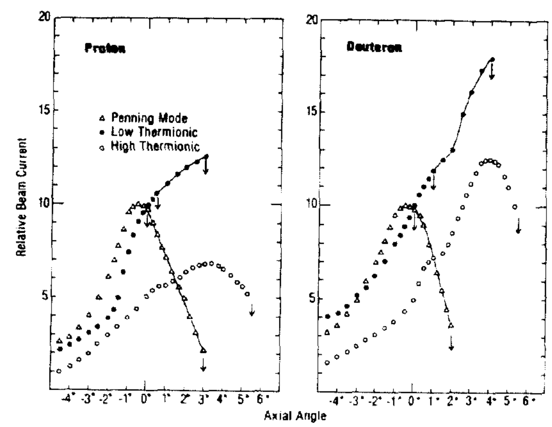


Fig. 5. Relative protons and deuterons beam current as a function of axial rotation.

to the fact that the arc column moves away from the extraction slit.

When the Penning mode is used, beam current peaks around zero degrees for all four particles. On the clockwise side, the beam current also decreases for all four particles. The arc current shows a step function type of dependence with the angular rotation. The beam current suddenly drops to zero as indicated by a downward arrow. The angular position at which the arc extinguishes is, in turn, strongly dependent on the gas flow and the arc voltage used. Increasing gas flow and arc voltage will allow the arc to survive at larger angle as shown by the data points linked by a solid line. The Penning mode beam current can be continuously adjustable at a given fixed dee voltage by adjusting arc voltage, gas flow and axial angle. The range of beam current output depends strongly on the type of particle, from a few picoamperes to a few hundred microamperes for protons and deuterons but to only a few microamperes for $^3He^{++}$ and $^4He^{++}$. When low thermionic arc is used, the beam current continues to increase as the ion source is rotated clockwise. Further rotation would turn the thermionic arc into Penning mode or zero arc current stage, the beam current would drop to a lower level or to zero accordingly. 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 slight, only 20 to 30 percent over the normal output at zero degrees. However, the variation of beam current level per unit change of axial angle is large. A small misalignment of the anode would give rise to an appreciable fluctuation in beam current output between servicing of the ion source. The rotational method is able to compensate this error.

For the high thermionic mode operation, quite a different charateristic is seen. Here the beam current of protons and deuterons go through a shoulder and then peak around 3 to 4 degrees. For $^3He^{++}$ and $^4He^{++}$, the beam current increases very rapidly from 3 degrees to 5.5 degrees where the arc extinguishes just before the arc column is totally blocked up. A remarkable improvement of beam current over 300% is obtained.

Gas flow dependence

As in the case for all P.I.G. sources, ion production increases when the gas flow is increased at low arc power. At high arc power the reverse is true. We observe some differences in gas flow dependence characteristics between different particles when high arc power and high power density is used. There is a very slight improvement of protons and only about 20% for deuterons. For doubly charged ^3He and ^4He, however, the improvement is significant. This is shown in Fig. 6 for ^3He case. At a gas flow of about 3 c.c./min., the beam current does not show much increase before 3 degrees, and only about 200% increase at 5 degrees. At a gas flow of 2 c.c./min. the rate of increase is much stronger. The total improvement of beam current is up to 600%.

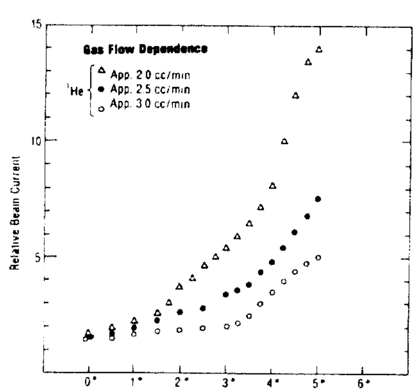


Fig. 6. Relative beam current output as a function of gas flow and axial angle.

Internal Beam Current

The improvement of doubly charged ^3He and ^4He beam current is most apparent after our rotational mechanism was developed. Fig. 7 shows the performance of the internal ^3He output as a function of RF dee voltage. Curve 1 and 2 were the maximum and routinely available output when non-rotational unit was used in the past. Dee voltage must be used to adjust beam current level. As a comparison, curve 'a' represents the optimum output achieved when the rotational method is ultilized. Curve 'b' is the routinely available beam current. Fig. 8 shows the routinely available deuterons and alpha beam currents. Here 400 microamps of alphas have been obtained as compared to about 50 microamps previously achieved. The optimum deuteron beam currents using low and high thermionic modes are also shown. The rate of increase per unit increment of dee voltage at the high thermionic mode seems to be equal for both deuterons and alphas, and faster than that of the low thermionic mode.

Fig. 7.

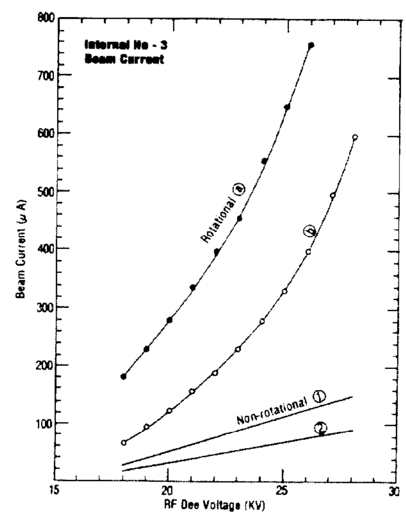
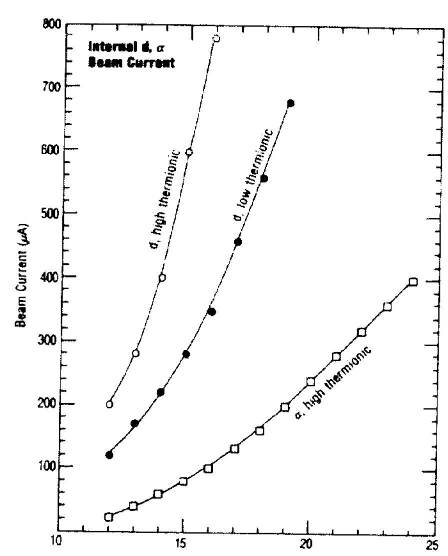


Fig. 8.



Discussion

The results we obtained here showed that higher ion production can be achieved by increasing the arc power density either with (Penning mode) or without (thermionic mode) adding more total arc power. The increase of ion production depends on the type of particle under study. For the four types of particle which can be accelerated with our compact cyclotron, the improvement is only slight for protons, but about 150% for deuterons, 400% for $^3He^{++}$ and 600% for $^4He^{++}$. The effect of increased ion production on the beam current output was reduced in our case due to the fact that the arc column retreated away from the extraction slit. The characteristics of the relative beam current as a function of axial rotation (Fig.4 and 5) were therefore structure dependent. A qualitative explaination of these behaviors will be given in a separate report. We believe that further improvement on our ion source can be made if the slit is located closer to the arc column when the power density is increased by rotational method.

The adjustable power density technique might be able to improve the yield probability of heavy ions at higher charge states. The question raised by Bennett and Gavin (3), as to why their ion source operated so well at relatively low power, might also be answered. For the high power P.I.G. ion sources (10-30 KW) used for the production of multiply charged heavy ions, the method to vary the power density would have to be more ellaborate. An ion source capable of dissipating 30 KW and providing a power density over a range from 30 to 300 KW/cm^2 might give us some new information.

The overall performance of our compact cyclotron has been greatly upgraded due to the success of the development of a more powerful and versatile ion source. High beam currents (200-400 μA internal, ^{3}He) have been routinely used for the production of ^{52}Fe (5). A method to produce ^{52}Fe and ^{18}F simultaneously has also been developed. In order to handle the large beam current safely many old controls have been modified and improved, and new ones developed (6). These efforts resulted in easier operation, greater controllability, lower level of maintenance and reduced frequency of breakdown. The overall extraction efficiency has been improved from 40±10% to 70±10%. External beams of about 200 uA of ^{3}He, 300 μA of ^{4}He and 400 μA of deuterons have been extracted on external targets, providing a beam current capability for higher production rate of radioisotopes and neutrons. The possibility of using neutrons for therapeutic treatment for cancer patients is being investigated.

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; for example, a few picoamps to 400 microamps of $^4He^{++}$ at 24 KV. This is an improvement of even greater significance. It allows our operator to set up the cyclotron with preset control parameters determined by a given dee voltage. It is also possible to install an internal slit system to further improve the extraction efficiency and to obtain better energy resolution if required.

Acknowledgement

The authors wish to thank Dr. Tilbury of Sloan-Kettering Institute, Dr. Hendry of The Cyclotron Corporation and Prof. Blosser of Michigan State University for helpful discussions related to our program. Thanks also go to John Conti, Max Shufer and Ralph Matacchieri for their assistance in the maintenance and operation of the machine.

Reference

1. D.K. Wells, IEEE Trans. Nucl. Sci. NS-14, 3, 70 (1967).

2. C.E. Anderson and K.W. Ehler, Rev. Sci. Instr. 27, 809 (1956).

3. J.R.J. Bennett and B. Gavin, Particle Accelerators, Vol.3, pp.85-90 (1972).

4. J.R.J. Bennett, Proceedings of the Fifth International Cyclotron Conference, p.469 (1969)

5. R.S. Tilbury, J.P. Mamacos and J.S. Laughlin, Proceedings of the Fifth International Cyclotron conference, Uses of Cyclotrons, p.117, (1969).

6. T.Y.T. Kuo, M. Shufer, J. Conti, R. Lee and J.S. Laughlin, Proceedings of this conference.