Heavy ion acceleration in the IPCR 160 cm cyclotron

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ABSTRACT

In the IPCR 160 cm classical cyclotron the operating ranges of the magnet and rf system are 0·5 to 2 Wb/m^2 and 5 to 12 mHz respectively, and various particles of different mass to charge ratios from protons to Ne^{5+} ions can be accelerated with variable energy.

Electron bombarded hot cathode heavy ion sources for this cyclotron have been developed to produce C^{4+}, N^{4+}, O^{4+}, N^{5+}, and O^{5+} ions. At present these ions are produced in sufficient quantities under arc powers of 2 to 2·5 kW when N_2, O_2, or CO_2 gas is fed into the source at a flow rate of 1 to 2 cm^3/min. The source life is mainly limited by the erosion of the tungsten cathodes to $\sim$20 h.

In this paper the attenuation of beam current by charge exchange collision with residual molecules and the spectra of various ions accelerated in the cyclotron are discussed.

C^{4+}, N^{4+}, and O^{4+} ions are accelerated from 39 to 120 MeV, 45 to 100 MeV, and 52 to 100 MeV respectively and used for several experiments.

1. INTRODUCTION

The IPCR 160 cm classical variable energy cyclotron was designed to accelerate several multicharged heavy ions such as C^{3+}, C^{4+}, N^{4+}, N^{5+}, O^{4+}, and O^{5+}, as well as protons, deuterons and α-particles without harmonic acceleration. The electromagnet and the oscillator system of this cyclotron have wide operating ranges of 0·5 $\sim$ 2 Wb/m^2 and 5 $\sim$ 12 MHz respectively as shown in Fig. 2.

Also, multicharged heavy ion sources have been developed to produce C^{4+} N^{4+}, and O^{4+}, etc., in adequate quantities under stable operation.

Acceleration of heavy ions has been tried in the cyclotron since autumn 1966 and at present C^{4+}, N^{4+}, and O^{4+} etc. are accelerated with sufficient intensity as shown in Table 1.
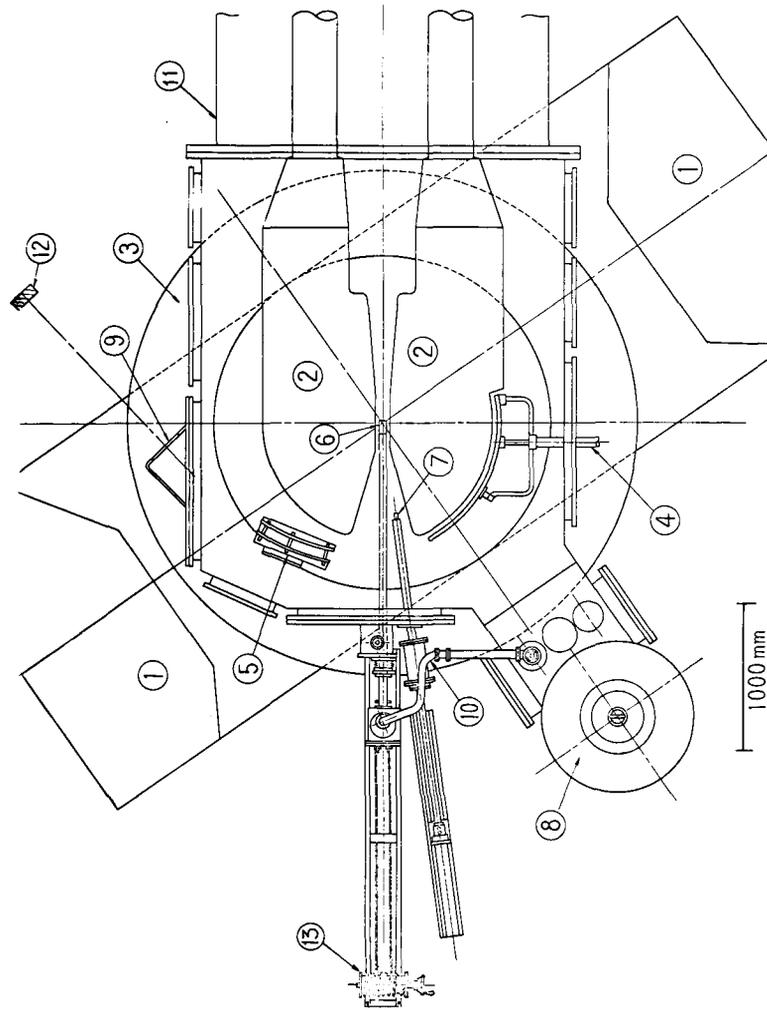
Fig. 1. Plan view of the accelerating chamber and its surroundings. 1—side yoke, 2—dees, 3—coil tank, 4—rf-deflector, 5—beam focusing magnetic channel, 6—ion source, 7—beam probe, 8—32-in oil diffusion pump, 9—beam exit flange, 10—exhaust pipe for ion source, 11—resonator tank, 12—gate drop probe, 13—winch

Fig. 2. The resonance condition of the IPCR 160 cm variable energy cyclotron. Radius at beam exit is 74 cm

Table 1. PROJECTILES, ENERGY RANGE, AND PARTICLE YIELD

Projectile	C^{3+}	C^{4+}	N^{4+}	N^{5+}	O^{4+}	O^{5+}
Energy (MeV)	39–75	39–120	45–100	45–160	52–100	52–140
Maximum current (μA)*	5	4	5	1	2	0·4

* Maximum beam current extracted from the cyclotron.

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In this report the production of multicharged heavy ions and some problems encountered in their acceleration are described.

2. MULTICHARGED HEAVY ION SOURCE

2.1. *Construction of new type source*

The new type source which is an improved version of an older design[1] is now operating satisfactorily.

Fig. 3 is a cross-sectional view of the source which is of the electron bombarded hot cathode type similar to Morozov's.[2] The arc plasma is established between tungsten cathodes K_1 (10 mm diam., 8 mm length) and K_2 (10 mm diam., 15 mm length). An arc chamber is constructed of a water cooled copper block and a copper chimney (84 mm length, ID 6 mm, OD 12 mm) which has a source aperture (3 mm $\times$ 10 mm). This chimney can be easily exchanged when the aperture has been eroded by ion bombardment. The gas is introduced into the arc chamber through several small holes (3 mm diam., 5 mm apart) from the distribution plenum (ID 4 mm) which is provided at the side of the chimney.

The tubes carrying the filament and cathodes are held in the horizontal arms T by steatite spacers. The innermost spacer is covered with steatite sleeves to protect it from being coated with sputtered tungsten.

As a filament for electron bombardment a 2 mm diam. tungsten wire is used, which is stong enough not to be bent by the Lorentz force in the strong magnetic field.

Two copper boxes (B in Fig. 3) are welded to the anode block which has a copper cooling tube. This anode system can be easily exchanged by loosening the joint (J) and separating the cooling pipe.

To prevent sparking in the supporting tubes, there are pumping ports, Q (15 mm $\times$ 30 mm) near the top of the supporting tube and a by-pass vacuum pipe at the end box of the supporting tubes, connected to the oil diffusion pump of the cyclotron. The stainless supporting tubes on the new type ion source are not cooled but there has been no trouble.

2.2. *Source operation*

Heavy ions, N^{4+}, N^{5+}, C^{4+}, O^{4+}, and O^{5+}, were accelerated in the cyclotron. For production of nitrogen ions, nitrogen gas was introduced to the ion source, and for carbon and oxygen ions, CO_2 gas and oxygen gas respectively. The electron bombardment power required was about 500 W (1·2 kV $\times$ 0·4 A).

The source was operated with arc voltages (V arc) of 250 to 400 V and arc currents (I arc) of 3 to 8 A, and then the arc power was 1·5 to 2·4 kW. The life of the source was limited by erosion of the upper cathode. When the source was operated at an arc power of about 2 kW, the source life was about 20 h, but the source was working again one hour after exchanging only the upper cathode. The cathode erosion occurred at about 0·35 g/h. The yield of ion beam extracted from the ion source and accelerated in the cyclotron was measured with an inner beam probe and a gate drop probe (Fig. 1).

Fig. 5 shows the variation of yields of N^{4+}, N^{5+}, and C^{4+} versus the gas flow rate for various constant arc voltages and currents.
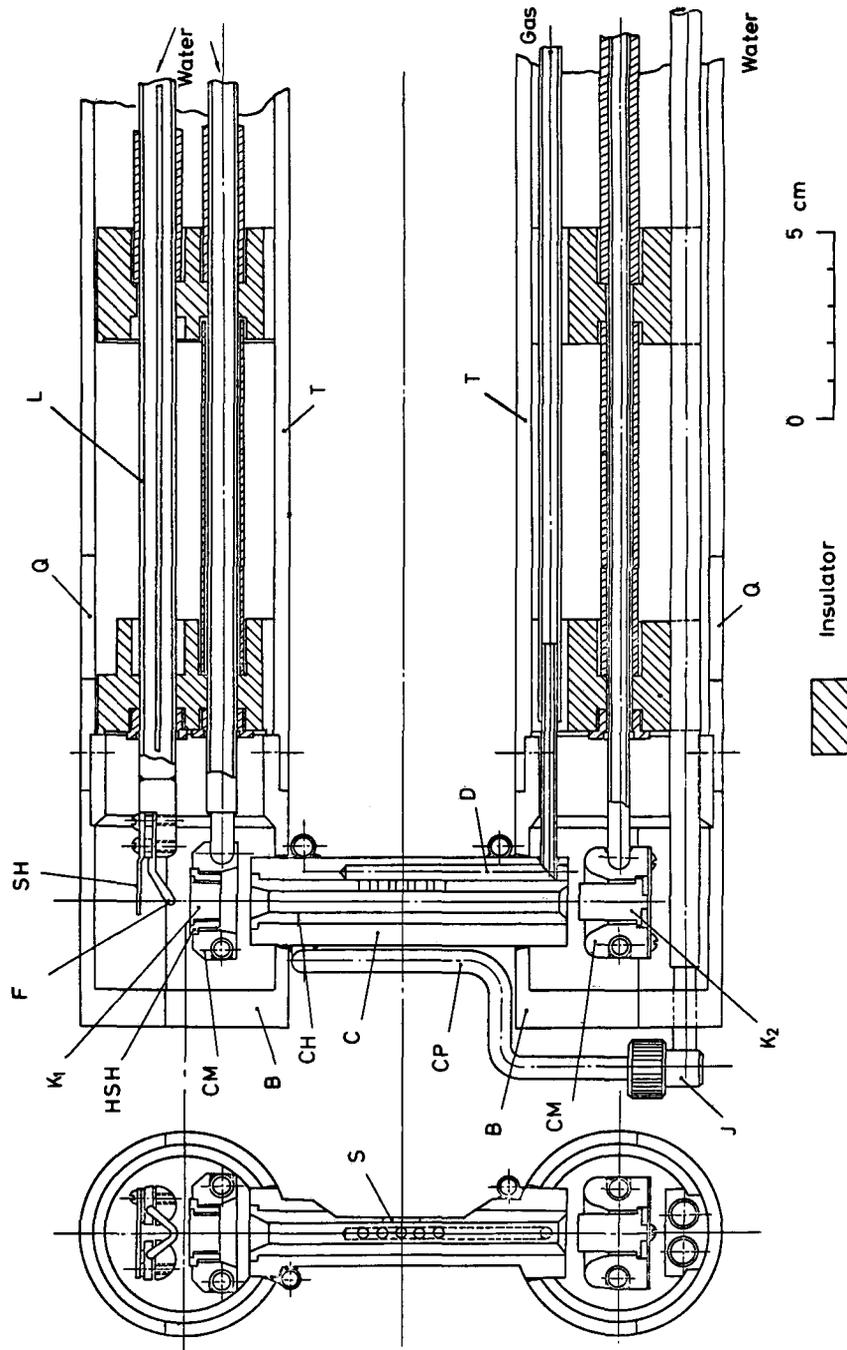
Fig. 3. Cross-sectional view of the ion source. K_1—hot cathode (W), K_2—reflector cathode (W),
CM—cathode mounting (copper and water cooled), SH—electron shield (Mo),
S—source aperture, C—anode block (copper, water cooled), D—distribution plenum,
CH—anode chimney (copper), B—anode box (copper), F—filament (W), Q—exhaust window,
J—cooling joint, T—tubular supporting arm, HSH—heat shield, L—filament lead,
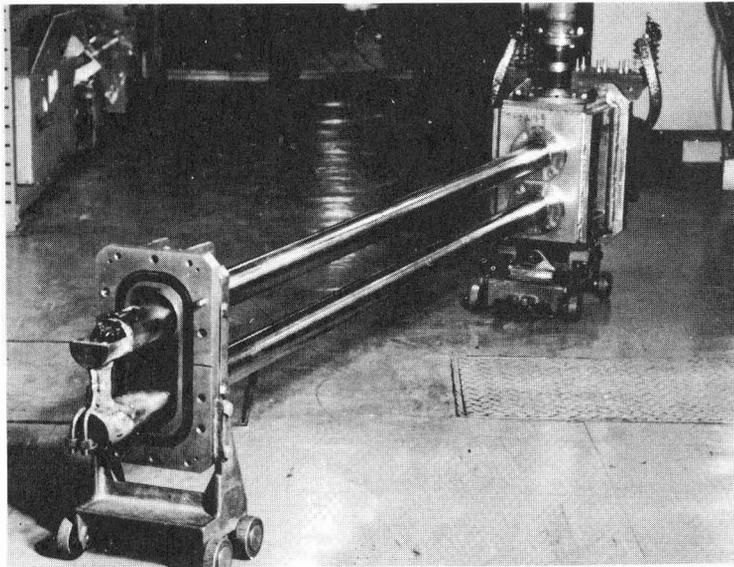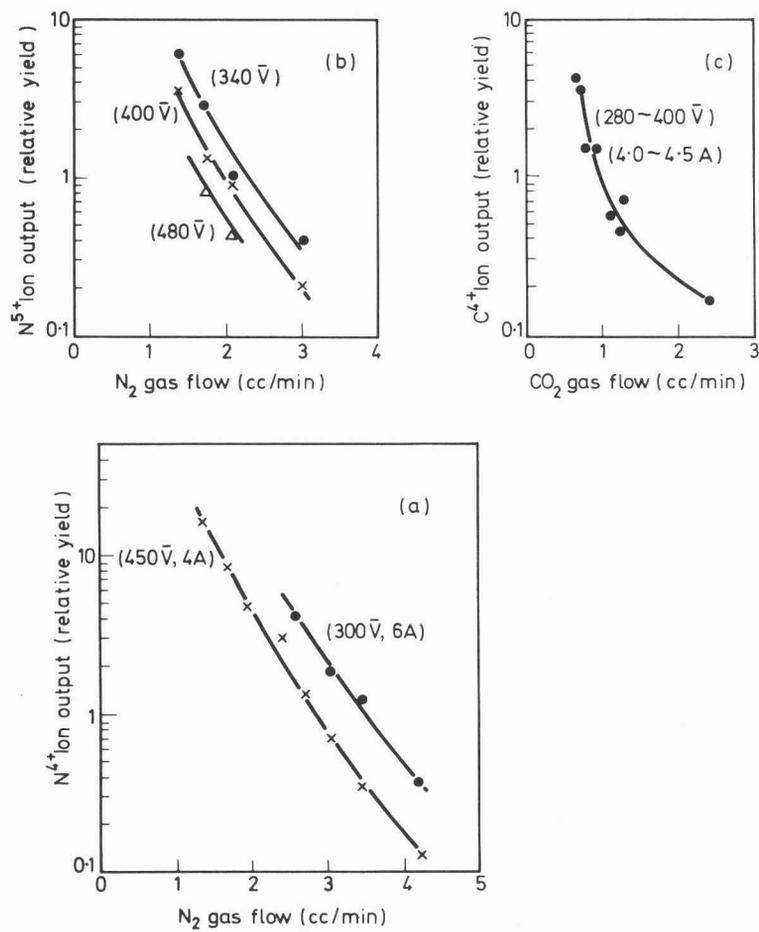CP—anode cooling pipe

Fig. 4. The ion source

Fig. 5. (a) N^{4+} ion relative yield vs nitrogen gas flow rate. (b) N^{5+} ion relative yield vs nitrogen gas flow rate. (c) C^{4+} ion relative yield vs CO_2 gas flow rate. In all cases voltages and currents are shown in parentheses
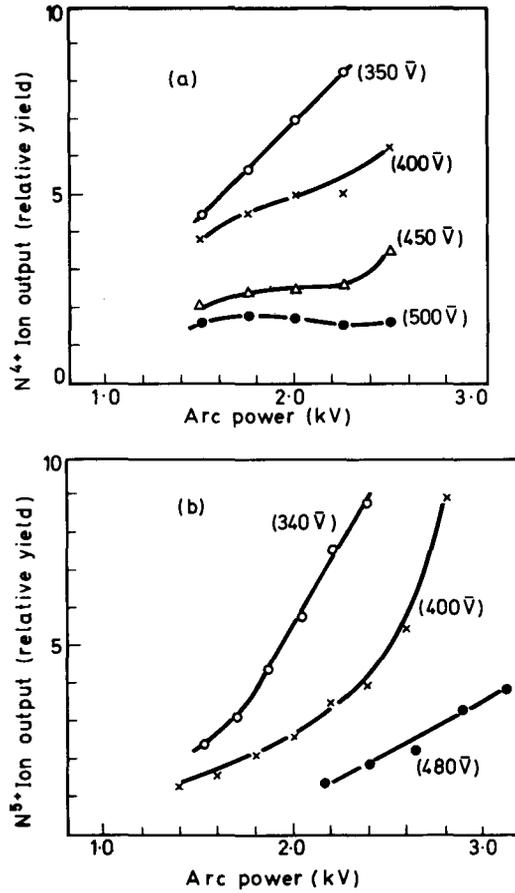
Fig. 6. (a) N^{4+} ion yield vs arc power. N_2 gas flow rate is 2·4 cm^3/min. Arc voltage is given in parentheses. (b) N^{5+} ion yield vs arc power. N_2 gas flow rate is 1·9 cm^3/min. Arc voltage is given in parentheses
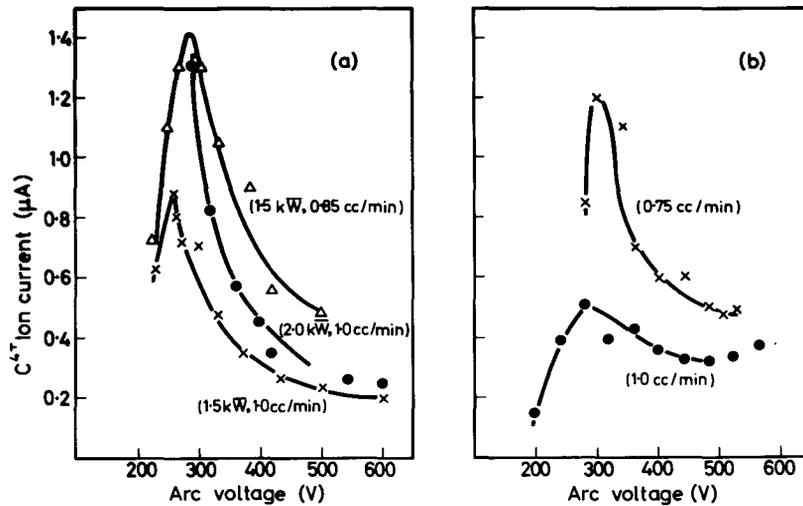

Fig. 7. (a) C^{4+} ion yield vs arc voltage. Arc power and CO_2 gas flow rate is given in parentheses. (b) C^{4+} ion yield vs arc voltage when the arc current is 5 A constant. CO_2 gas flow rate is given in parentheses. (Radius of beam probe position is 60 cm)

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In Fig. 5 it is shown that a smaller gas flow brings about a higher yield of multicharged ions, but to strike the discharge, a somewhat larger gas-flow is needed. Once the discharge is started, the gas flow is reduced as far as possible without extinguishing the discharge. The arc discharge of CO_2 gas was possible at a lower gas flow rate than that for N_2 gas.

Figs 6 and 7 show the variation of yields of N^{4+}, N^{5+}, and C^{4+} vs the arc power and arc voltage at various constant gas flow rates. These arc conditions for constant gas flow were produced by varying the electron bombardment power. Both N^{4+} and N^{5+} yields increased with the arc power and, especially, N^{5+} yield for the arc voltage of 340 V increased by a factor of about four when the arc power was varied from 1·5 to 2·4 kW. When the arc power was kept constant, both yields increased with increase of the arc current and decrease of the arc voltage to the optimum value. The C^{4+} yield, as shown in Fig. 7, became maximum at an arc voltage from 160 V to 300 V when the arc power was kept constant. In the case of oxygen ions, yield variations with gas flow, arc power, and voltage showed almost the same features as with nitrogen and carbon ions.

3. HEAVY ION ACCELERATION

3.1. *Accelerated heavy ions in the cyclotron*

In the source an arc plasma was established stably with N_2, O_2, CO_2, and Ne gases. To examine which multicharged heavy ions were accelerated in the cyclotron the m/q spectra of accelerated ion beams were measured with a beam probe fixed at the radius of 65 cm by varying the magnetic field strength from 0·5 to 2 Wb/m^2 under the condition of constant oscillator frequency and dee voltage.

The spectrum measured is shown in Fig. 8(a) when CO_2 gas was fed into the source. In these figures (3), (5), and (7) mean the harmonic numbers of the acceleration modes. In this case, four kinds of beams are measured at relatively
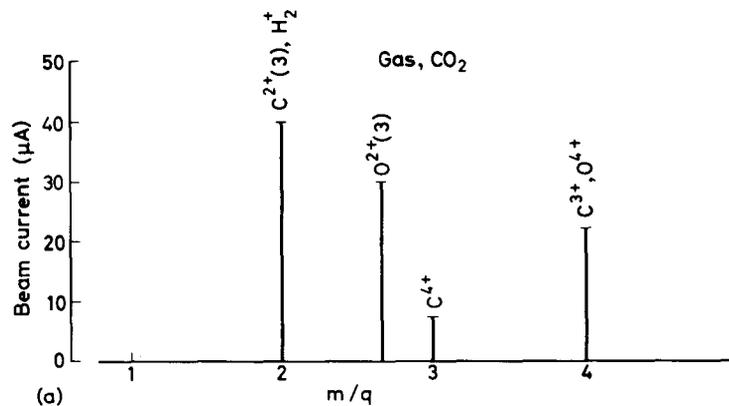

Fig. 8. m/q *spectrum of various ion beam (radius of beam position 65 cm). (a)* CO_2 *gas discharge;* f = 7·078 Mc/s, Vd = 60 kV, Arc 360 V 3·1 A; *(b)* N_2 *gas discharge,* f = 6·468 Mc/s, Vd = 47 kV, Arc 320 V 3·4 A; *(c)* O_2 *gas discharge,* f = 6·48 Mc/s, Vd = 50 kV, Arc 410 V3·5 A; *(d)* Ne *gas discharge,* f = 6 Mc/s, Vd = 45 kV, Arc 410 V 4 A
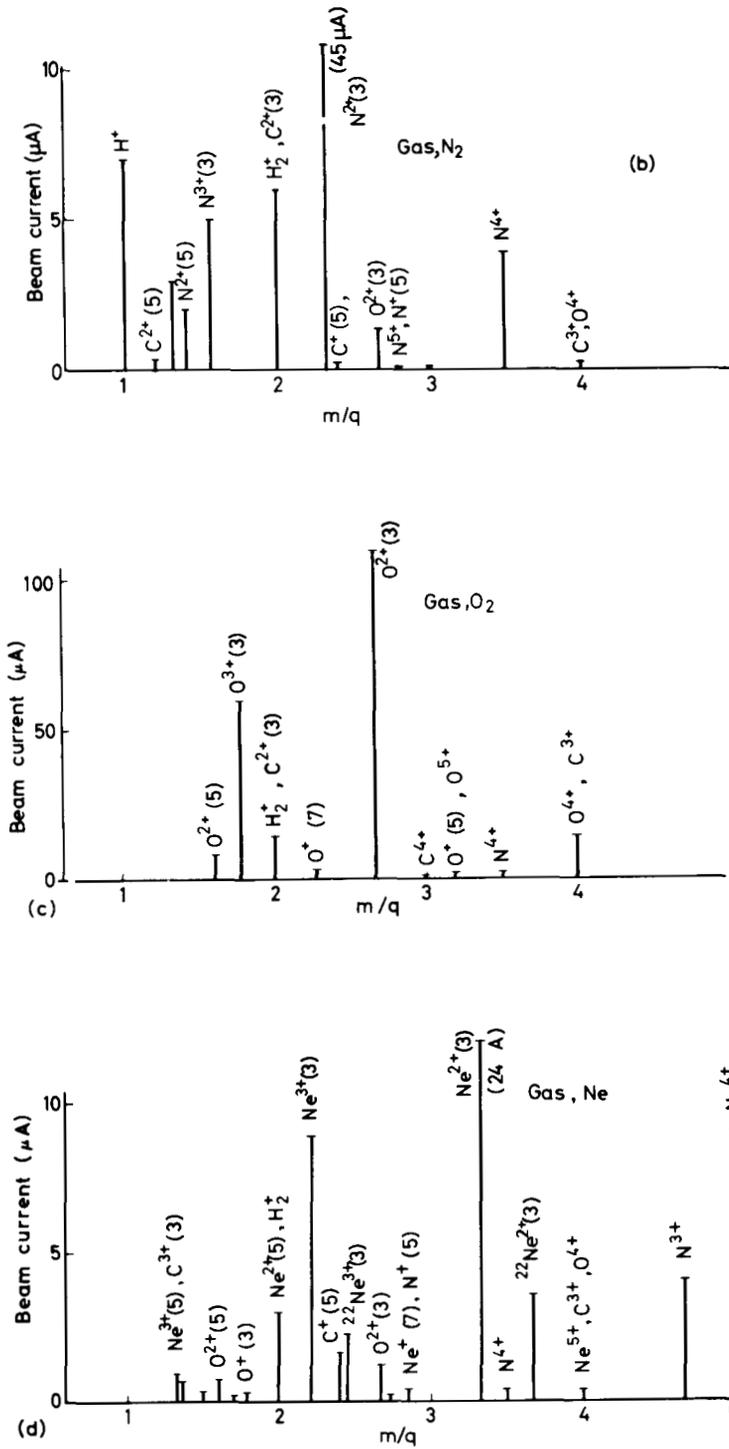
Fig. 8. (continued)

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high intensity. They are C^{2+} and O^{2+} ions accelerated with third harmonic frequency, C^{4+} ions and a mixture of C^{3+} and O^{4+} found at the ratio $m/q = 4$.

As shown in Fig. 8(b), it is found that the spectra not only of N ions but also of Ca and O ions are detected when N_2 gas is fed in the source. Carbon peaks may come from pump oil vapour, vacuum grease, or residual CO_2 gas, because the anode is made of copper.

Fig. 8(c) shows the spectrum of O_2 gas. The O ions are mainly detected but we can detect small quantities of C and N ions, too. O^{4+} and C^{3+} ions have the same ratio of m/q and cannot be distinguished. The contamination of C^{3+} ion to O^{4+} ion is estimated at about 5% by passing the deflected beam through a thin foil. If a pure oxygen ion beam is wanted, it is desirable to accelerate O^{5+} ion although its beam current is small.

Fig. 8(d) shows the spectrum obtained when Ne gas was fed in the source. In this case, not only ^{20}Ne ions but also a small amount of ^{22}Ne ions are detected. The N ion is also detected, and this is supposed to be due to the fact that the gas feed pipe has not been evacuated sufficiently after supplying the nitrogen gas. A small peak with $m/q = 4$ is assigned to a mixture of C^{3+}, $^{20}Ne^{5+}$ and O^{4+} ions. The ions accelerated on harmonics cannot be extracted from the cyclotron because in the rf-deflector only the dee voltage is employed for deflection.

3.2. Beam attenuation during acceleration (in relation to charge exchange effect)

The beam attenuation is not significant for protons, deuterons, and α-particles as shown in Fig. 9(a), but it is appreciable in the case of multicharged heavy ions as shown in Fig. 9(b). Collision with residual gas causes charge exchange that breaks down the resonance condition of the ions.

Fig. 10 shows the ratio of N^{4+} beam current measured at 70 cm radius to that at 40 cm rad. (maximum radius is 74 cm) vs the pressure of the accelerating chamber of the cyclotron. It is found that the ratio decreases rapidly with the pressure. The pressure of the chamber was varied by adjusting the nitrogen gas flow introduced into the ion source. In Fig. 10, abscissa the pressure of the
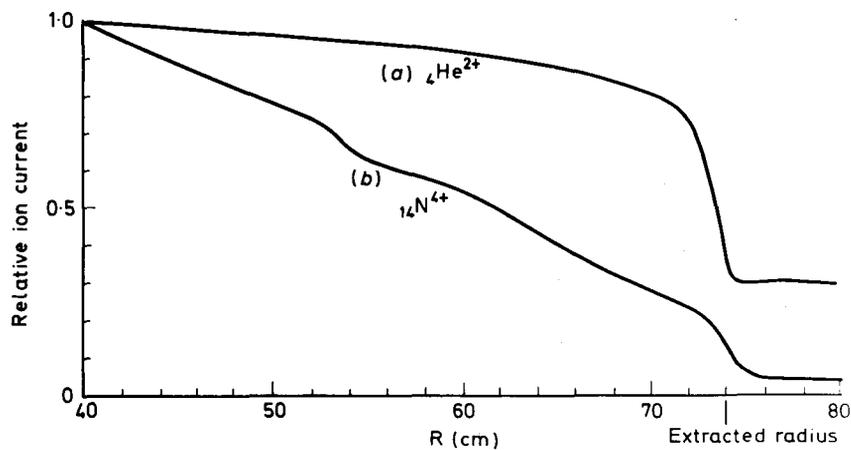

Fig. 9. Beam attenuation

accelerating chamber near the diffusion pump is shown, but it is found that the pressure in the dees, where the ions are accelerated, is $3 \sim 4$ times larger than that in the chamber.

It is possible to calculate the attenuation due to charge exchange, knowing the cross-section data, the path length of the ions in the cyclotron, and the pressure in the dees.
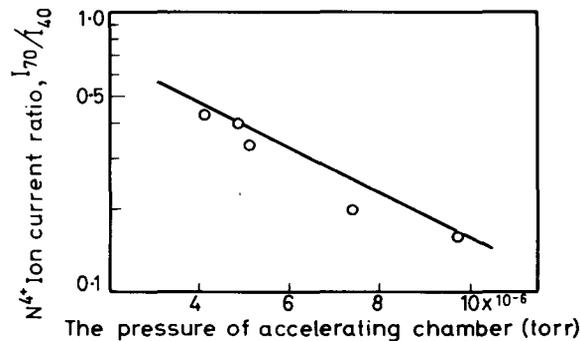

Fig. 10. Beam attenuation caused by charge exchange effects, as a function of the pressure in the accelerating chamber. I_{70}/I_{40} is the ratio of the beam intensity at 70 cm from the centre of cyclotron to that at 40 cm

In Fig. 10, the solid line represents the result of the calculation using the charge exchange cross-section data measured by Dmitriev[3] and by us, and it agrees well with the measured value.

If the beam attenuation is to be less than a half, it is necessary for the pressure to be less than 4×10^{-6} torr. Under normal conditions the pressure in the chamber is $2 \sim 4 \times 10^{-6}$ torr.

4. CONCLUSION

The ion sources for multicharged heavy ions developed in this laboratory are used for studies of nuclear reaction, nuclear chemistry, radiation chemistry, and biology with good reliability. The special features of the source are mechanical rigidity of the chimney and good vacuum in the supporting tube to prevent discharges. The source is operated continuously for about 20 h and easy to recondition within 1 h.

The operating conditions that affect the yield of multicharged ions, such as gas flow, arc voltage, and arc current, have been examined. When the gas pressure in the chimney is low, the yield of multicharged ions increases.

In the ion source it is supposed that multicharged heavy ions are mainly produced by stepwise ionisation, because the quantities of C^{4+} and N^{4+} reach maximum values at the relatively low arc voltage of 250 to 300 V under constant arc current.

Spectra of the accelerated beams have been presented. The beam intensities of low charged ions accelerated in the harmonic mode are larger than those of highly charged ions accelerated in the fundamental mode with the same dee voltage.

The attenuation of the ion beam current caused by charge exchange has been

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shown. It depends on the pressure in the cyclotron and the path length of the ions. Therefore, it is necessary for the acceleration of heavy ions that the pressure in the cyclotron be low and the dee voltage high.

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