The production and acceleration of heavy ions in the Harwell variable energy cyclotron

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ABSTRACT

The design and performance of the ion source for the Harwell Variable Energy Cyclotron is described. The source is of the Penning Ionisation Gauge Type, having solid tantalum or tungsten cathode discs which are heated directly by the discharge. The arc is operated continuously and not pulsed. Preliminary results of laboratory tests of a simple modification to the source to produce multiply charged ions of solid materials are also presented.

The source is inserted axially into the cyclotron through a slot in the top pole of the cyclotron magnet and is positioned by a precision mechanism to obtain centred orbits. The source has been in regular use in the cylotron and has produced beams of hydrogen, helium, carbon, nitrogen, oxygen, neon, argon, and krypton ions. Of particular note are the extracted beams of 2 μA of 150 MeV N^{5+} ions, 10 μA of 120 MeV C^{4+} ions, and 0·08 μA of 180 MeV C^{5+} ions. Very low energy heavy ion beams have been accelerated on fifth and seventh harmonics and currents of the order of one microampere of beam extracted despite the poor geometry at the centre of the cyclotron. The cyclotron vacuum is adequate to keep beam loss due to stripping down to a reasonable level, though with some low velocity beams the stripping is severe.

1. INTRODUCTION

The Harwell Variable Energy Cyclotron[1] is a three ridged isochronous machine built to accelerate protons up to an energy of 50 MeV and heavier ions up to energies given by

$$E = 84 \frac{q^2}{A} \text{ MeV}$$

where q and A are the charge and mass of the ion in proton charge and mass units. The acceleration of heavy ions was an important feature from the

500

inception of the machine and a source was designed at an early stage to produce multiply charged heavy ions.

The ion source was designed to be inserted axially through the top pole of the cyclotron to reduce congestion around the cyclotron vacuum chamber. The geometry also lends itself to accurate source positioning. Furthermore the source is changed in a shielded room above the cyclotron magnet where radiation levels are much lower than in the cyclotron vault.

2. THE MULTIPLY CHARGED HEAVY ION SOURCE

2.1. *Source design*

The ion source[2], shown in Fig. 1, is of the Penning Ionisation Gauge type, having two solid tantalum or tungsten cathode discs and a copper anode. The anode is water cooled and contains a replaceable slit plate of tungsten to resist erosion by ions accelerated back to the source on the positive half cycle of the rf voltage on the cyclotron dee. The anode is at ground potential and a negative voltage is applied to both cathodes. The cathodes are supported on insulated holders; the upper one is water cooled. The lower cathode connection is made by a rod coming from below the source through the bottom pole of the cyclotron, locating in a socket attached to the lower cathode support. Although this support is not water cooled, the cathode assembly will withstand the temperatures produced, even when the cathode is brought to melting point.

The slit apertures are changed to suit the beam currents required. The total extracted current does not vary linearly with area until the dimensions of the aperture are much greater than the thickness (0.02 in) of the plate. Usually over 0.2 A/cm^2 can then be obtained. Most experiments in the laboratory tests are carried out with slits ¼ in high by $\frac{1}{32}$ in or $\frac{1}{16}$ in wide, and currents up to 20 mA obtained with 20 kV extraction voltage. In the cyclotron slits up to $\frac{3}{8}$ in high and $\frac{1}{8}$ in wide are used.

2.2. *Modifications for solid materials*

A simple modification of the source described above is being developed to obtain multiply charged ions of solid materials. The material to be ionised is placed inside the anode chamber opposite the ion extraction slit. A discharge is started up, using hydrogen or some other gas, which heats the material to a temperature where it begins to evaporate. The arc current is regulated to obtain the required rate of evaporation.

Although this method does not give independent control of the heating of the materials and the arc conditions, good percentages of multiply charged ions have been obtained. Moreover, the method is simple, robust, requires no extra controls, and the source is no bulkier than the standard one used for gases. The use of an oven, as in many solid material sources, attached to the back of the anode would not be possible since it would make the source too large to fit in the cyclotron.

Tungsten, tantalum, molybdenum, carbon, boron nitride and silica inserts have been used in the form of tubes, $\frac{7}{8}$ in long, cut away along the side facing the extraction slit. Low melting point materials are placed in a slot cut in a tantalum tube insert. Lithium, calcium, iron, and copper have been used this way.

ELECTRICAL CONNECTION
AND WATER COOLING PIPE
TO UPPER CATHODE

COPPER CATHODE SUPPORT

BORON NITRIDE INSULATOR

TANTALUM CATHODE

ANODE WATER
COOLING

GAS FEED

COPPER ANODE

TUNGSTEN SLIT PLATE

TANTALUM CATHODE

MOLYBDENUM CATHODE
SUPPORT

BORON NITRIDE INSULATOR

1 INCH

SOCKET FOR
ELECTRICAL CONNECTION
TO LOWER CATHODE
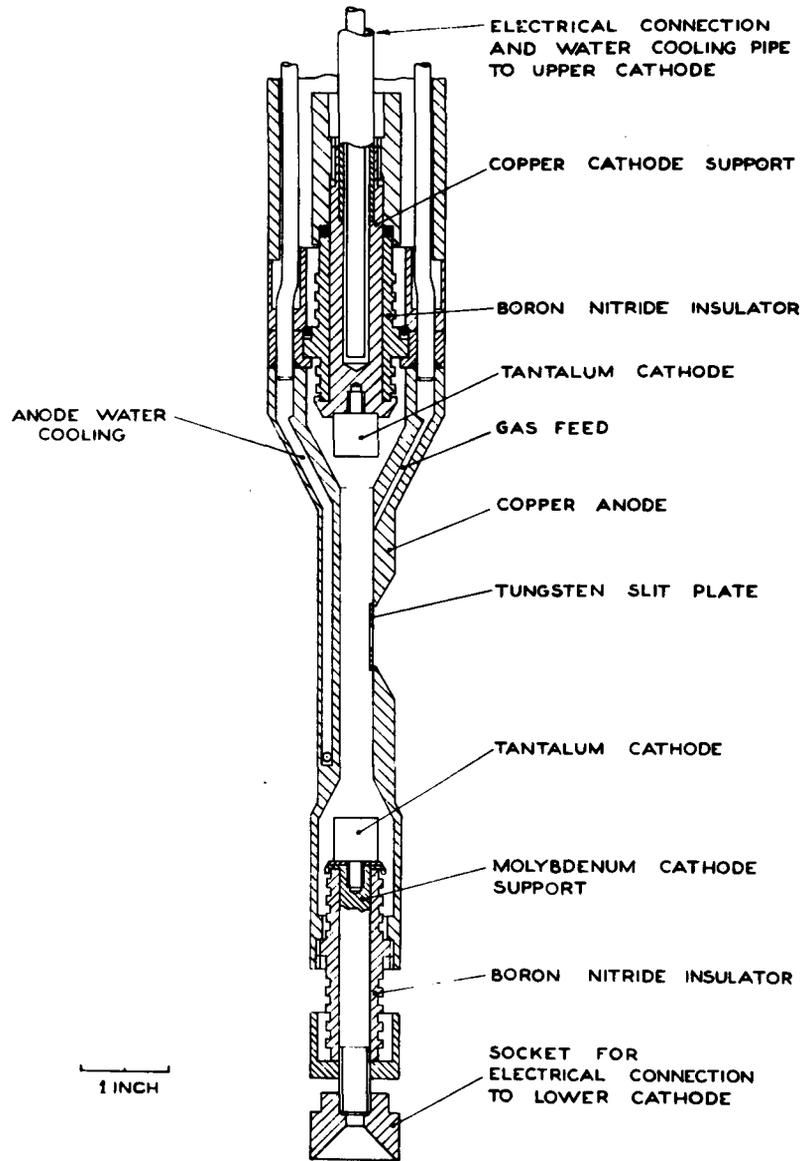
Fig. 1. Section through the multiply charged heavy ion source

502

The source has not been operated in the cyclotron but may be used in the axial injector in which case the solid materials emanating from the source will not be deposited in the cyclotron.

2.3. Operation

To start the discharge between 1·5 kV and 3 kV is applied to the cathodes, the gas flow being raised to about 2 to 5 st.cm^3/min to keep this voltage as low as possible. Once the arc has struck the gas flow may be reduced to the operating level, and the arc current adjusted to suit the beam required. These two parameters, gas flow and arc current are the only two variables and make operation of the source very simple.

The output of multiply charged ions rises steeply at low arc gas pressures. Fig. 2 illustrates this point. Precise control of the gas flow is therefore very important.
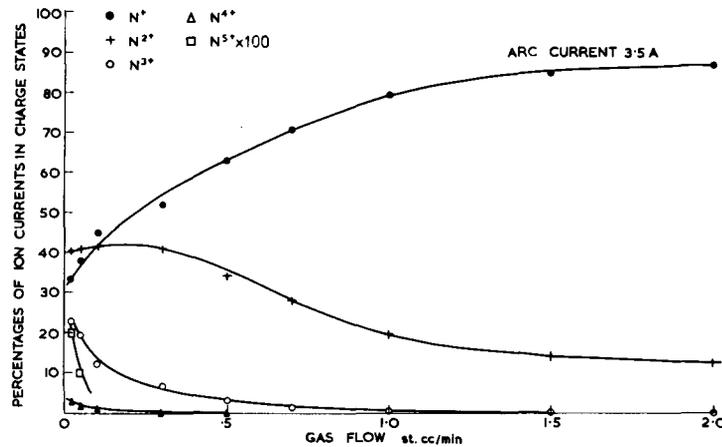
Fig. 2. Variation in percentage of nitrogen ion currents with gas flow at constant arc current

The source has proved to be robust and the simple design which does not involve auxiliary cathode heating or filaments is an advantage. The anode, which must be cleaned every time the cathodes are renewed does not suffer from wear and will last for years if carefully treated. The cathodes may be replaced very easily and quickly. The life of the cathode varies greatly with the gas and the conditions of the arc. With hydrogen gas many hundreds of hours life can be expected, but with nitrogen only about 20 h, whilst with argon it is as little as 8 h.

2.4. Laboratory performance

All the laboratory tests of the ion source have been carried out in a 180° magnetic spectrometer. Table 1 shows the percentages of ion current in different charge states for a few gases (commercial grades of gases are used). Also shown in the table are the arc conditions under which the source was run for the particular

Table 1

Gas	Arc voltage (V)	Arc currents (A)	Gas flow (st.cm³/min)	Ion	Percentage of ion current in charge state								
					1	2	3	4	5	6	7	8	9
Hydrogen	160	9.5	1.5	H₁	98.8								
				H₂	1.2								
				H₃	0								
Helium	720	5.5	0.4	He	85	15							
Carbon monoxide	1600	3.5	0.45	C	11.1	22.9	7.9	1.2	0.003				
				O	11.2	20.8	16.4	8.2	0.3	0.007			
Nitrogen	730	8	0.15	N	15.8	37.0	37.0	9.6	0.6	0.006			
Oxygen	500	4	0.5	O	25.7	35.4	30.1	8.0	0.8	0.01			
Neon	350	9	~0.01	Ne	11.4	43.0	36.1	8.0	1.6	0.02			
Argon	800	2	~0.01	A	6.4	16.5	33.0	33.0	7.9	2.4	0.6	0.1	
Krypton	600	2	~0.01	Kr	9.0	26.1	32.7	17.0	9.1	5.0	0.78	0.26	
Xenon	660	2.5	~0.01	Xe	0.8	7.1	20.9	21.0	19.4	14.6	11.2	4.9	0.03

Table 2

Solid	Arc voltage (V)	Arc current (A)	Support gas flow (st.cm³/min)	Percentage of support gas ion current	Ion	Percentage of ion current in charge state							
						1	2	3	4	5	6	7	8
Lithium	700	2	0.2	18	Li	94.23	5.65	0.12					
Boron nitride	900	2.25	0.1	70	B	68.3	29.3	2.4					
Calcium	700	2	0.1	—	Ca	34.0	58.8	6.8	0.4				
Iron	700	4.5	0.2	29	Fe	14.3	41.2	24.2	12.2	6.05	2.06		
Copper	250	5.5	1.4	—	Cu	33.6	42.3	14.9	8.1	1.1	0.1		
Tantalum	250	17.5	0.1	90-95	Ta	4	16	24	24	12	8	6	4

504

results. These conditions are not unique and in particular the gas flow will vary with the size of the slit in the anode.

Most of the development work has been carried out with nitrogen gas, and the performance is very encouraging, 0·6% of N^{5+} being found and a trace of N^{6+}. Usually 0·3% of N^{5+} is easily obtainable.

There is little difficulty in producing protons: over 98% of the hydrogen beam can be protons. By suitably adjusting the arc conditions up to 60% of the beam can be composed of H_2^+ or H_3^+ ions.

Table 2 shows some preliminary results for the solid material source. The percentages of ion current in the various charge states do not include the current from the support gas. A separate column lists the fraction of the ion current from the support gas in the beam. It should be stressed that these results are only preliminary. The figures for tantalum are approximate and finish at the eighth charge state only because of confusion with the support gas which in this case was argon.

3. ACCELERATION OF HEAVY IONS IN THE V.E.C.

3.1. *The central region geometry of the V.E.C.*

The cyclotron has a single 180° rf dee and a grounded dummy dee. The separation of the dees is 2 in to accommodate the fairly large ion source. The movable puller in the dee mouth is usually set to about 0·3 in from the source slit.

The source is accurately positioned by a mechanism[3] mounted on the top pole of the cyclotron. A rotatable centre plug in the pole has a radial slot to allow the source to move to different offsets to obtain centred beams. A further two slots in the plug at 120° maintain the three-fold symmetry of the magnetic field.

3.2. *Performance*

Table 3 gives a list of some of the heavy ion beams which have been accelerated over the last three years. One energy for each ion species has been selected. The currents quoted are not necessarily the best available. For example, the 24 MeV C^{3+} beam was run for only a short time and not properly developed or extracted. On the other hand, C^{4+} and N^{5+} beams have been well developed and currents are typical values now routinely obtained. Internal currents have been quoted at 30 in radius, just before the extraction radius. In some cases where stripping losses are severe these values do not reflect the true currents accepted by the cyclotron from the ion source.

To obtain reasonable currents of the rare ions such as N^{5+}, a large source slit, $3/8 \times 3/32$ in is used. Although the total current emerging from the source cannot be measured directly in the cyclotron, it is proabably about 50 mA during the peak of the rf accelerating cycle. Most of this beam is of unwanted ions which are not accelerated properly. A computed path of the unwanted ions indicates that many of them hit the back of the source with an energy equivalent to acceleration through the voltage amplitude on the dee. Some of the beam hits the dee and puller. With the large beams the puller breaks down more readily to the ion source. Otherwise, operation with heavy ions is no more difficult than with protons.

Table 3.

Particle	Energy (MeV)	Internal beam current (µA)	Extracted beam current (µA)
C^{2+} (third harmonic)	22	52	30
C^{3+} (third harmonic)	24	4·5	1
C^{4+}	118	18	10
C^{5+}	175	0·15	0·08
N^{+} (seventh harmonic)	3	20	1·5
N^{2+} (fifth harmonic)	7	3·6	1
N^{4+}	98	over 100 (current limited by permissible dissipation of probe)	30 (current limited by permissible dissipation of septum)
N^{5+}	150	4	2
O^{3+} (third harmonic)	47	36	12
O^{4+} (third harmonic)	32	33	10
Ne^{3+} (third harmonic)	38	45	10
Ne^{4+} (third harmonic)	65	13	7·5
A^{8+} (third harmonic)	130	0·04	0·02
Kr^{5+} (fifth harmonic)	27	2	0·2
Kr^{8+} (third harmonic)	64	0·5	—

3.3. Harmonic acceleration

Acceleration of beams on harmonics of the rf is used to increase the low energy range of the cyclotron. With the large gap between the dees necessary to accommodate the ion source, the central geometry is poor for harmonic acceleration since the gap factors become very low as the harmonic number increases. However, satisfactory acceleration of ions on third harmonic is routinely achieved with extraction efficiencies of about 50%.

The ability of the cyclotron to accelerate ions on higher harmonics has also been demonstrated despite the poor centre geometry. Beams of N^{2+} and Kr^{5+} ions have been accelerated on fifth harmonic and N^{+} ions on seventh harmonic. All three beams were extracted. The internal beam quality and centring was poor and the extraction efficiency suffered accordingly. The beams were much more sensitive to the centre orbit coils, indicating that they did many turns in the centre before receiving good acceleration in the dee gaps.

It was not possible to measure the efficiency of the acceleration of these beams on fifth and seventh harmonic directly in the cyclotron. However, an estimate can be obtained knowing the source performance under similar conditions from the laboratory test results. Generally on fundamental mode about one-tenth of the d.c. beam from the source is accelerated to full radius in the cyclotron, and third harmonic mode is about one-third as efficient as fundamental. For the particular fifth and seventh harmonic cases chosen the calculated efficiencies are both about 1/1000, or 100 times less efficient than fundamental and 30 times less than third harmonic. These efficiencies do not necessarily reflect the true values relative to fundamental operation since a comparison should be carried out on fixed orbits.

506

3.4. Beam attenuation due to charge exchange

Loss of beam due to charge exchange by collision with residual gas atoms in the cyclotron vacuum chamber is not generally severe. The vacuum pressure indicated on ionisation gauges is between 1 and 2×10^{-6} mm of mercury. The gas flow from the ion source does not usually increase this pressure by more than 1×10^{-6} mm of mercury.

Attenuation of high energy beams is very small. Fig. 3 shows a beam current
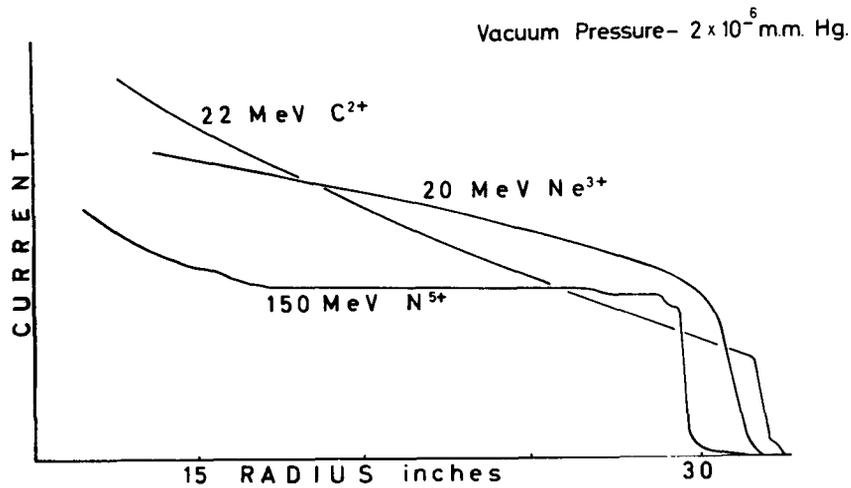
Fig. 3. Beam attenuation due to charge exchange. Variation of beam current with radius in the cyclotron for 150 MeV N^{5+}, 20 MeV Ne^{3+}, and 22 MeV C^{2+} at a pressure of 2×10^{-6} mm of Hg. (The extractor was limiting the maximum radius of the N^{5+} beam)
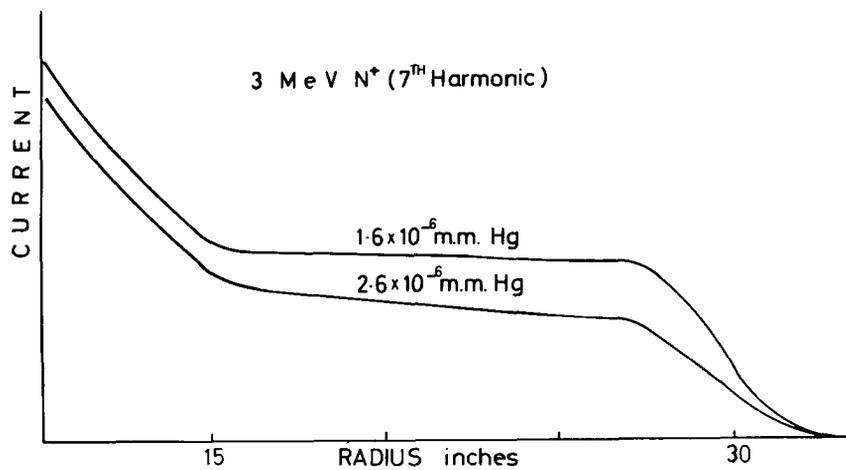
Fig. 4. Variation of beam attenuation with pressure. Plots of beam current vs radius for 3 MeV N^+ (seventh harmonic) showing charge exchange losses at two pressures

507

vs radius plot for N^{5+} ions accelerated to 150 MeV. At the beginning of the acceleration the cross-section for pick-up of an electron is high but fortunately the ions are quickly accelerated to high velocities where the pick-up and loss by charge exchange cross-sections are relatively low. It is not possible to measure the loss in the region near the centre of the cyclotron because of the stray beams of ions in other charge states. In particular N^+ ions are accelerated on fifth harmonic to a radius of approximately 17 in before becoming completely out of phase with the rf voltage. The N^+ beam can be seen on Fig. 3: sometimes the cut-off is very sharp, depending on the machine settings.

At very low energies the attenuation of the beam can also be very small. Fig. 4 shows a N^+ ion beam accelerated to 3 MeV on seventh harmonic. Although the charge exchange cross-section is high—about 5×10^{-16} cm^2—the particles have a very short path length in the cyclotron. Fig. 4 also shows the effect of changing the pressure in the cyclotron by almost a factor of two. The small drop in current at 15 in radius suggests that attenuation at the centre is not very great.

For ion beams of intermediate energies the stripping loss can be quite marked. Fig. 3 shows a Ne^{3+} ion beam accelerated to 20 MeV. The charge exchange cross-sections are similar to those of the 3 MeV N^+ beam but the number of turns is over four times greater, giving a corresponding increase in path length and attenuation. The figure also shows a 22 MeV C^{2+} beam. Other fairly low velocity beams such as 130 MeV A^{8+}, 27 MeV Kr^{5+}, 64 MeV Kr^{8+}, and 47 MeV O^{3+} suffer from stripping losses.

Estimates of cross-sections from the attenuation of the beams in the cyclotron agree well with published figures[4] for experimentally determined cross-sections within the uncertainties of the true pressure in the cyclotron and the nature of the residual gas.

ACKNOWLEDGEMENTS

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