Ion sources for multiply charged heavy ions

J. R. J. Bennett
Rutherford High Energy Laboratory, Chilton, Berks, England

ABSTRACT

A review is given of existing sources of multiply charged heavy ions. Particular emphasis is on cyclotron applications. Most sources are of the P.I.G. type and the performance of the various models is compared.

New methods have recently been suggested for producing high charge states of very heavy particles. Some are based on plasmas used in thermonuclear research. A very brief account is given of a few of these devices.

Finally, acceleration and stripping of ions is mentioned for completeness, as it can be a very effective way of producing highly charged ions.

1. INTRODUCTION

Highly charged heavy ions are needed if high energies are to be produced without building massive accelerators. Unfortunately these ions are difficult to produce and a compromise must usually be made between the charge state and the size of the accelerator. There are a few cyclotrons which accelerate ions of masses up to about 20 amu to energies up to 10 MeV/nucleon. Linear accelerators extend the range to particles up to mass 40. With the increasing interest in accelerating the very heavy particles a number of proposals have been made for constructing large accelerators or of producing very highly charged ions in plasma devices.

The more conventional ion sources used in accelerators are based on gas discharges where the ionisation is mainly caused by energetic electrons. An alternative way to produce multiply charged ions is to accelerate a low charged ion and pass it through a small quantity of matter where some of the electrons are removed. The stripped ion is then accelerated to a high energy. There are several proposals, some of which are presented at this conference, involving cyclotrons as one or both of the accelerators in this system. Stripping is already used in heavy ion linear accelerators and electrostatic generators.

This paper will attempt to review the more conventional ion sources and to mention some of the new devices for producing highly charged heavy ions.

CYC69E05

2. P.I.G. SOURCES

Of the many types of ion sources the Penning Ionisation Gauge[1] discharge has been the most successful in producing multiply charged heavy ions. There are several variations of this type of source.

2.1. *The Floating Cathode P.I.G. Source*

The Floating Cathode P.I.G. Source has one cathode isolated whilst the discharge potential is applied between the other cathode and the anode. The configuration is convenient for a cyclotron since the electrical connections need only be brought to the one cathode. This type of ion source has been used for many years in cyclotrons to produce light ions, being known as the Livingston[2] source. The 'live' cathode must be a hot filament emitting electrons otherwise the discharge will not strike. The floating cathode takes up a potential near to that of the opposite cathode giving rise to a typical P.I.G. discharge. Fig. 1 shows a section through the floating cathode source[3] used on the Harwell Variable Energy Cyclotron It is a close copy of the source Ehlers[4] designed for the Berkeley 88 in cyclotron.

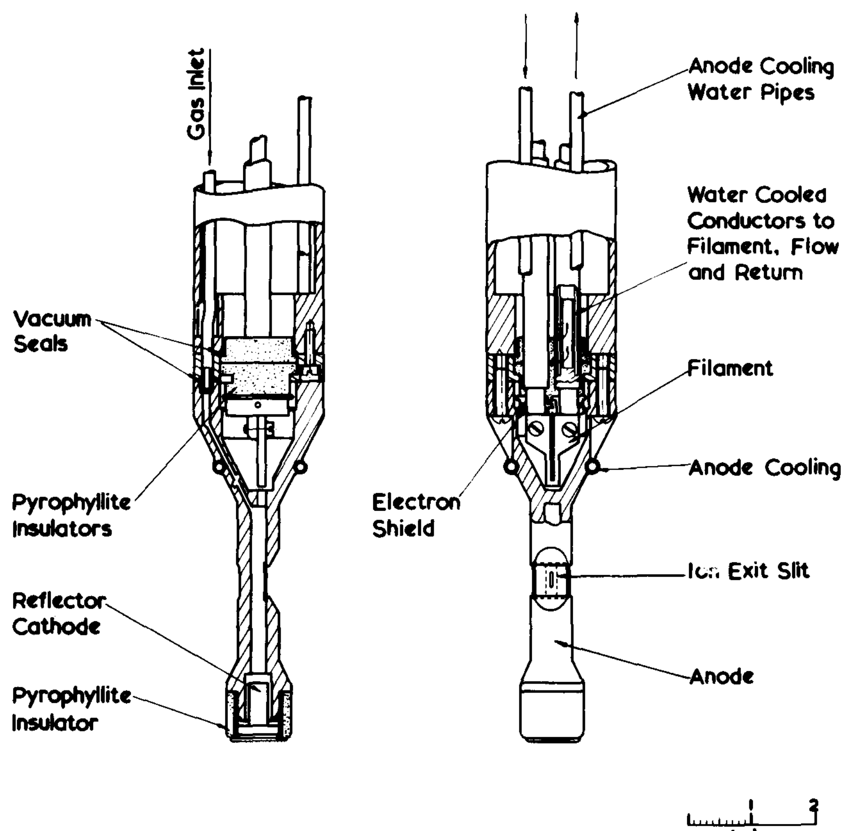

Fig. 1. Floating Cathode P.I.G. Source. This source[3] is a close copy of the Berkeley 88 in cyclotron source developed by Ehlers[4] and used for a short time in the Harwell Variable Energy Cyclotron

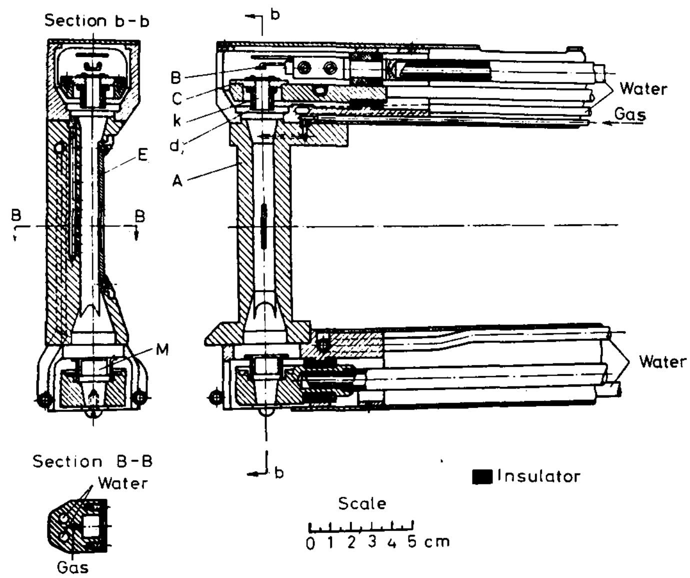

Fig. 2. Indirectly Heated Hot Cathode P.I.G. Source. The figure shows the source originally developed by Morozov, Makov, and Ioffe.[9] A – *Anode,* k – *Cathode,* B – *Filament for indirect cathode heating*

Jones and Zucker[5] developed two sources for multiply charged nitrogen ions from a high intensity proton source[2] for use in the Oak Ridge 63 in cyclotron. One source was a floating cathode type, the other had both cathodes electrically connected and is discussed in Section 2.2. The performance of the source was very good and is shown in Table 1. Internal beam currents of over 100 μA of N^{3+} ions were accelerated[6] in the cyclotron to 24 MeV. A very similar source is being used now to produce heavy ions in the Oak Ridge Isochronous Cyclotron (ORIC) and is reported[7] elsewhere in this conference.

Ehlers[4] has developed a source of this type for the Berkeley 88 in cyclotron which operates on a variety of gases including hydrogen and oxygen. The source is in regular use on the cyclotron for light ions, but little work has been done on heavy ion acceleration, although 0·3 μA of 100 MeV N^{4+} ions have been extracted.

2.2. *Hot Cathode P.I.G. Source*

This class of source has both cathodes connected together electrically and one or both cathodes are hot and emit electrons thermionically. Many cyclotron sources of this type have been made for heavy ions. Jones and Zucker[5] were the first to show its potential which they found superior to that of the floating cathode source for producing multiply charged ions. The source[8] used in the Harwell Variable Energy cyclotron is of this type.

The most common design, due to Morozov,[9] has an indirectly heated cathode and is shown in Fig. 2. The cyclotrons at Dubna have accelerated up to 50 μA of C^{4+}, 20 μA of N^{5+}, 20 μA of O^{5+}, 1 μA of Ne^{6+}, 0·01 μA of Ne^{7+}, 5 μA of A^{7+} and 0·5 μA of A^{8+} using this source design under pulsed conditions. These currents which are mean values at maximum radius in the cyclotron are impressive. The pulse is 1 ms long with a repetition frequency of about 250 c/s, the slit aperture in the source is 2 × 0·25 cm and the dee voltage 150 kV.

2.3. *Cold Cathode P.I.G. Sources*

These sources have the two cathodes connected together electrically but the cathodes remain relatively cool so that electron emission is mainly due to positive ion bombardment (secondary emission). Because of the high powers necessary for the production of multiply charged heavy ions all sources in this class are pulsed otherwise the cathodes would become hot. The cold cathodes make their characteristics different from the other sources in Section 2.1 or 2.2. For example the hot cathode sources have negative resistances whilst the cold cathodes have positive resistance characteristics.

Anderson and Ehlers[10] developed a source for the Berkeley and Yale heavy ion linear accelerators. Fig. 3 shows the source. An end extraction design[11] was used on the Manchester heavy ion linac. Instead of coming from a slit in the anode, the ions come from a small hole in the centre of one of the cathodes. Although the current densities at the extraction aperture are about 10 times higher than for side extraction the proportion of highly charged ions is less. Mineev and Kovpik[12] reported an end extraction source (Fig. 4) using plasma expansion which performed considerably better. However, a copy of this source built at the Rutherford Laboratory gave charge percentages similar to the Manchester source.

2.4. *Comparison of performance*

Table 1 lists the performance figures for a number of P.I.G. sources running on nitrogen gas. Nitrogen has been selected since it is the most commonly used gas and allows comparisons to be made. The figures are taken from the literature as shown by the reference numbers. Some of the results are presented in a different form to that in the original papers. In these cases the results have been adapted as well as possible from the information available. It is hoped that the list is at least representative of the P.I.G. sources but not necessarily exhaustive. The hot cathode sources are simply listed under P.I.G. and include the Morozov type with indirect cathode heating as well as those without. Under the heading 'Arc Conditions', are given the arc current and voltage under which the measurements were taken and, for sources operated under pulsed conditions, the pulse length is given.

Jones and Zucker[5] unfortunately do not give figures for N^{5+} but the percentages of N^{4+} ion currents are good and the N^{5+} current should have been appreciable. The P.I.G. source produces more N^{4+} ions than the floating cathode source and is operated at higher currents. The performance is not very dissimilar from that of the similar type of source of Bennett[8] and it is apparent that these sources have not advanced significantly over the last 15 years.

Of the Morozov type sources the original[9, 13] still appears to be better than the copies.

Pulsing the P.I.G. sources (all types) allows greater peak powers to be dissipated in the arc with consequent improvement in output of multiply

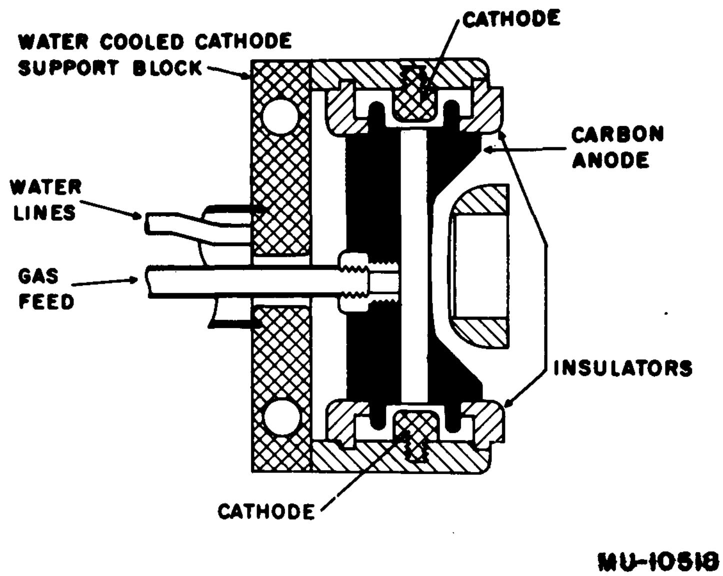

Fig. 3. Cold Cathode P.I.G. Source. The source used on the Berkeley Hilac, developed by Anderson and Ehlers[10]

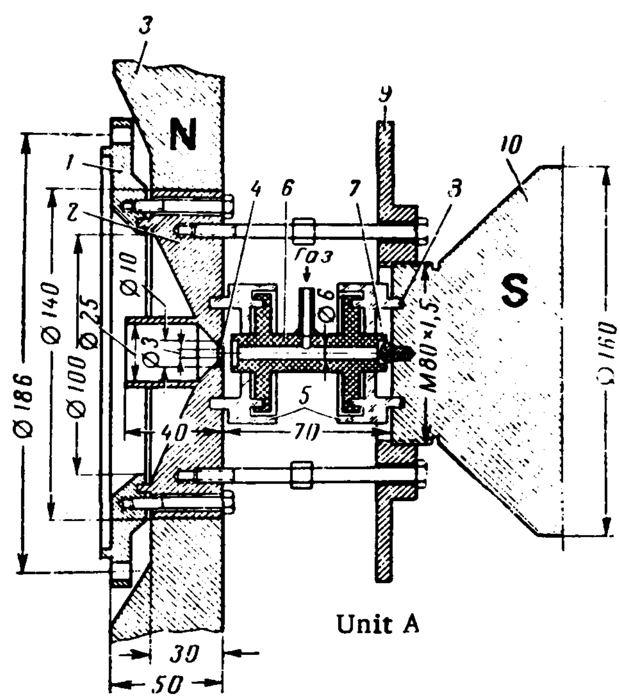

Fig. 4. Cold Cathode P.I.G. Source with End Extraction. The source developed by Mineev and Kovpik[12] *used plasma expansion for initial focusing of the ion beam. 3 and 10 – Poles of Electromagnet, 6 – Anode, 5 – Insulator, 7 – Cathode, 4 – Cathode with hole to allow expansion of plasma into the cup*

Table 1

Source type	*Authors*	*Arc conditions*			*Percentage of ion current in charge state*					
		Volts	Amps	ms	1	2	3	4	5	6
P.I.G. Floating Cathode	Jones and Zucker[5]	500	2·5	Continuous	42·6	41·3	12·9	3·4		
P.I.G. Floating Cathode	Ehlers[4]	350	1·5	Continuous	36	45	17	2		
P.I.G.	Jones and Zucker[5]	600	5·1	Continuous	28·2	31·4	30·4	9·8		
P.I.G.	Makov[13]	580	4·6	Continuous	25·2	39·9	29·0	5·5	0·4	
P.I.G.	Papineau, Benezech, and Maillard[14]	300 350	10 40	Continuous 15	40 22·2	46·6 41·8	12·3 31·4	1·0 4·6	0·05	
P.I.G.	Mavrogenes, Ramler, and Turner[15]	300	10	Continuous	22	42	31·2	4·2	0·15	
P.I.G.	Basile and Lagrange[16]	520	5	Continuous	33	33·5	30	3·5	0·15	
P.I.G.	Bennett[8]	730	8	Continuous	15·8	37·0	37·0	9·6	0·6	0·006
P.I.G.	Pigarov and Morozov[17]	800	24	0·02	9.2	21.7	35.0	20.0	14.1	
P.I.G. Cold Cathode	Anderson and Ehlers[10]	2000	1·3	2	47·8	42·4	8·5	1·2		
P.I.G. Cold Cathode End Extraction	Bennett[11]	2000	2	2	63	32	5			
P.I.G. Cold Cathode End Extraction	Mineev and Kovpik[12]	800	8	0·2	38·8	46·6	14·6			

Table 2

Source type	Authors	Ion	Arc conditions				Percentage of ion current in charge state											
			Volts	Amps	ms	c.p.s.	1	2	3	4	5	6	7	8	9	10	11	12
Duoplasmatron	Ilgen[23]	Kr	175	18	3	10	5·5	28·5	45·7	17·0	3·3							
(Heidelberg, Unilac)		Xe	295	31	3	10	6·6	20·2	29·0	19·4	14·2	7·5	3·4					
P.I.G.	Ghiorso, Main,	Kr	2000	1·5	2		8·3	14·9	16·5	19·2	16·2	13·9	5·8	2·5	2·0	0·66	0·17	
(Berkeley, Hilac)	and Smith[18]	Xe	2000	1·5	2		6·7	11·4	12·2	13·8	16·5	12·7	12·0	6·9	4·2	2·5	0·8	0·4
P.I.G.	Passiouk,	Kr	450	12·7	1	100	4·3	10·3	23·6	25·8	19·3	10·7	4·3	1·5	0·1	0·01		
Hot Cathode	Tretiakov, and Gorbatchev[19]	Xe	600	13	1	100	1·8	5·5	14·8	16·6	17·5	16·6	12·9	11·0	2·4	0·7	0·2	0·05
P.I.G.		Kr	2000	1·5	1	100	25·6	23·0	16·9	14·1	9·5	6·4	2·6	1·2	0·7	0·2		
Cold Cathode		Xe	2000	1·5	1	100	23·6	19·6	16·5	12·5	9·9	6·4	5·7	3·1	1·7	0·9	0·2	0·1
P.I.G.	Bennett[8]	Kr	600	2·0	Continuous		9·0	26·1	32·7	17·0	9·1	5·0	0·78	0·26	0·03			
(Harwell V.E.C.)		Xe	660	2·5	Continuous		0·8	7·1	20·9	21·0	19·4	14·6	11·2	4·9				

charged ions. This is shown in the results of Papineau *et al*[14] where pulsed and continuous performance figures are given for a Morozov type source. With very short pulse lengths Pigarov and Morozov[17] were able to obtain very significant increases in the output of multiply charged ions, and obtained over 14% of N^{5+} ion current. The output of N^{6+} is not mentioned.

The cold cathode sources of Anderson and Ehlers[10] and Bennett[11] were built for linear accelerators where relatively low charge states are required – N^{3+} and N^{2+} respectively. Their performance for high charge states is generally inferior to the other sources. The end extraction source of Bennett was particularly poor, but Mineev and Kovpik[12] have produced good fractions of high charge states. The fraction of ions in charge states above N^{3+} are not given.

With heavier particles such as argon, krypton and xenon the cold cathode sources are better for producing the highly charged ions. Table 2 shows the performance of the Berkeley Hilac source[18] developed by Gavin from the original source of Anderson and Ehlers. The performance of a Morozov type source[19] when pulse operated with hot and cold cathodes is also shown. Krypton and xenon gases have been selected to enable comparisons to be made. The pulse length and frequency are indicated under 'arc conditions'. It is seen that the cold cathode sources have a flatter distribution of ions in the various charge states and greater fractions of the ions in the highest charge states. This is particularly noticeable with the Hilac source which although operating under the same arc current and voltage conditions as the Dubna source of Passicuk, Tretiakov and Gorbatchev gives much greater fractions of current in the highest charge states.

Operation of the P.I.G. sources with cold cathodes results in higher arc voltages and lower arc currents than with hot cathodes. For ions such as Kr^{9+} and Xe^{9+} the ionisation potentials are over 200 V and arc voltages of 1000 V or more are desirable to optimise the possibility of ionisation. This may explain the more rapid fall off of the fraction of ions in the charge states over eight for the hot cathode source. However, the total ion yield is dependent on the arc current so that the actual current of ions may in some cases be larger for the hot cathode source. The currents quoted by Passiouk for a source slit of $1{\cdot}5 \times 0{\cdot}1$ cm are 22 μA of Kr^{10+} and 100 μA of Xe^{12+} from the hot cathode source but only 12 μA of Kr^{10+} and 10 μA of Xe^{12+} from the same source operated with cold cathodes. The Hilac source has obtained 40 μA of Kr^{10+} and 26 μA of Xe^{12+}.

For comparison the performance of the Harwell cyclotron source is shown for krypton and xenon. With continuous operation the power input is much reduced and the performance is poor for the highest charge states.

2.5. *Possible improvement*

Over the last 10 to 15 years there have been no major improvements in the design of P.I.G. sources. The sources developed by Jones and Zucker[5] and Anderson and Ehlers[10] are still basically unaltered.

Improvements could probably be gained if the arc current and voltage could be increased. This is shown by the work of Pigarov and Morozov[17] using very short pulses when a high arc voltage could be maintained under heavy current conditions. Since much of the arc power is dissipated in the cathodes more effective cathode cooling would be required. Already the cathodes are being operated at high power densities and surface evaporation would soon become a problem even with pulsed operation and water cooled cathodes.

Another problem that would be increased with higher arc powers is that of cathode erosion by heavy ion bombardments. This is already severe with the heavier ions and governs the life of the source. It might be possible to develop a source with 'plasma' cathodes. Dawton[20] has used a mercury pool arc in place of the filament to supply electrons for a duoplasmatron source. The 'filament' life is almost infinite.

3. SPARK SOURCES

Sparks are sources of very hot plasma and are well known to contain highly ionised particles.[21] Few sources have been constructed using this method. They must of course be pulsed. Bolotin[22] *et al,* describes a spark source used for a linear accelerator. Two per cent of the total nitrogen ion current was as N^{4+}. The maximum current which could be obtained was 15 mA during the 15 μs pulse, of which only 30% was composed of nitrogen ions.

4. DUOPLASMATRON SOURCES

Von Ardenne[23] described a source in 1956 which produced 0·95 mA of N^{3+} ions and 0·06 mA of N^{4+} ions in a pulsed discharge from a 1 sq mm aperture. Until recently little work has been carried out on the duoplasmatron. The Heidelberg heavy ion linear accelerator group have been investigating the source for producing highly charged krypton and xenon ions. The results[24] are shown in Table 2 and may be compared with the P.I.G. sources. The low arc voltage probably prevents the production of the higher charge states. No information is given for nitrogen ions, but neon compares unfavourably with the results of P.I.G. sources, the majority of current being in the singly charged state.

5. ELECTRON BEAM SOURCE

An intense, magnetically focused electron beam is used by Donets, Ilyushchenko and Alpert[25] to produce highly ionised particles in an ultra high vacuum of 10^{-9} mm Hg. The positive ions are trapped in the electron beam for up to 20 ms before the beam becomes space charge neutralised. Successive ionisation of the trapped ions occurs and charge states C^{5+}, N^{6+}, O^{7+} and Au^{19+} have been observed. Completely stripped carbon nitrogen and oxygen cannot be detected because of confusion with H_2^+ ions. Electron beam densities up to 8A/cm^2 at up to 7 keV are used. The device, known as EBIS, is hoped to be developed to give 5 μA of uranium ions with a charge state of 38 for use in the 300 cm Dubna cyclotron where they can be accelerated to 2 GeV.

6. PLASMA SOURCES

Highly charged ions have been observed in a number of plasmas concerned with thermonuclear research. For example Peacock[26] claims to have observed A^{17+} in a high density pinch experiment. Most of these devices are pulsed with very short duty cycles. For use in an ion source some containment mechanism is required with a controlled leak of ions to give an output over a reasonable length of time. Although there is considerable interest in these devices to produce very highly charged heavy ions no working sources have been constructed.

At Oak Ridge interest is being shown in a device known as ELMO[27] where useful currents of highly charged ions are predicted by single impact ionisation. No measurements have yet been made on the charge state distribution.

Peacock and Pease[28] have suggested producing a plasma by irradiating a solid particle with an intense light pulse from a *Q*-spoiled laser. Spectroscopic analysis of the plasma reveals highly ionised iron particles with charges up to 15. By using magnetic confinement of the plasma a pulse up to 1 ms long could be produced. The yield would be about 10^{13} ions/s with charge states between 10 and 20.

Tonon and Rabeau[29] have also produced multiply charged ions with a laser produced plasma. Ions up to C^{4+} and Mo^{7+} were reported.

The 'Hipac' source,[30] reported later in this conference, is predicted to be capable of producing 10^{13} ions/s for Kr^{20+} and 10^{11} ions/s of U^{60+}. An electron cloud contained by a toroidal magnetic field forms a potential well to trap positive ions. The electrons rotate perpendicularly to the magnetic field with an energy of about 10 keV and produce highly stripped ions. Containment times of over 0·1 seconds are required to build up the required degree of ionisation and the vacuum pressure must be very low in the region of 10^{-10} mm Hg. Ions could be fed out of the containment device over 5–10 ms.

7. STRIPPING

Although not strictly regarded as an ion source, the acceleration and stripping of particles to high charge states is an important process. It can be quite efficient, particularly if the energy is high so that the majority of ions are full stripped.

Stripping has been used in cyclotrons.[31, 32] Ions are accelerated on a harmonic of the radio frequency. Some of the ions are stripped by collisions with the residual gas in the vacuum chamber to a charge state which allows acceleration on the fundamental mode to a higher energy. The process occurs randomly in the cyclotron and the beam quality of the stripped ions is very poor, resulting in low extraction efficiencies.

More efficient acceleration is achieved by accelerating the particles in a separate machine before stripping. A linear accelerator, near completion at Orsay,[33] is to accelerate ions of charge to mass ratio $\geqslant 0{\cdot}1$ to 1 MeV/nucleon. The beam is injected on the median plane of the cyclotron where it is stripped by a thin foil and accelerated on the correct orbit centre. In this way Kr^{21+} for example, will be produced and accelerated to 370 MeV.

8. CONCLUSIONS

It is possible to produce ions with charge to mass ratios of 0·3 to 0·35 up to mass 20 directly from ion sources. Cyclotrons of moderate size can accelerate these ions to energies of about 10 MeV/nucleon. P.I.G. sources have so far proved most capable of producing highly charged ions. It seems unlikely that they can be developed further to produce the very high charge states of the heavier elements such as uranium to enable acceleration to 10 MeV/nucleon in the present cyclotrons. Large accelerators, using stripping techniques must be built, or new sources such as those derived from plasmas used in thermonuclear work, laser sources, the 'Hipac' source or the electron beam source must be developed for use with existing cyclotrons. Until these sources have been shown to work, the large accelerator complexes using stripping are more likely to be constructed.

REFERENCES

1. Penning, F. M., *Physica,* **4,** 71, (1937).
2. Livingston, R. S. and Jones, R. J., *Rev. Sci. Instr.,* **25,** 552, (1954).
3. Bennett, J. R. J., Rutherford Laboratory Memo. NIRL/M/80.
4. Ehlers, K. W., *Nucl. Instr. Meth.,* **18, 19,** 571, (1962).
5. Jones, R. J. and Zucker, A., *Rev. Sci. Instr.,* **25,** 562, (1954).
6. Reynolds, H. L. and Zucker, A., *Rev. Sci. Instr.,* **26,** 894, (1955).
7. Lord, R. S., *et al,* Proceedings of this Conference, p. 453.
8. Bennett, J. R. J., Proceedings of this Conference, p. 499.
9. Morozov, P. M., Makov, B. N., and Ioffe, M. S., *Atomaya Energiya,* **3,** 272, (1957).
10. Anderson, C. E., Ehlers, K. W., *Rev. Sci. Instr.,* **27,** 809, (1956).
11. Nassibian, G., *et al. Rev. Sci. Instr.,* **32,** 1316, (1961).
12. Mineev, F. I. and Kovpik, O., *Prib. Tekh. Eksp.,* **8,** 33, (1963).
13. Makov, B. N., J.I.N.R. Transactions of the Conference on Nuclear Reactions with Multiply Charged Ions. March 1958. A.E.C.–tr–4445.
14. Papineau, A., Benezech, P. and Maillard, R., *J. Physique Rad.* **21,** 410, (1960).
15. Mavrogenes, G. S., Ramler, W. J., and Turner, C. B., *I.E.E.E. Trans. Nucl. Sci.,* **NS-12,** 769, (1965).
16. Basile, R. and Lagrange, J-M., *J. Physique Rad.* **23,** 111A, (1962).
17. Pigarov, Y. D. and Morozov, P. M., *Soviet Phys.-Tech. Phys.,* **6,** 336, (1961).
18. Ghiorso, A., Main, R. M., and Smith, B. H., *I.E.E.E. Trans. Nucl. Sci.,* **NS-13,** 280, (1966).
19. Passiouk, A. S., Tretiakov, Y. P., and Gorbatchev, S. K., J.I.N.R., Dubna, Report No. 7-3370 (1967).
20. Dawton, R, H. V. M., *Nucl. Instr. Meth.,* **24,** 285, (1963).
21. Eden, B., *Zeit. fur Astrophys.,* **22,** 30, (1942).
22. Bolotin, L. I., Markin, P. S., Kulygin, Y. F., Skoromnii, G. M., and Meleshkov, S. I., *Prib. Tekh. Eksp.,* **6,** 88, (1961).
23. Von Ardenne, M., *Atomkern-Energie,* **4,** 121, (1956).
24. Illgen, J., University of Heidelberg, Unilac Group Report 4-68.
25. Donets, E. D., Ilyushchenko, V. I., and Alpert, V. A., J.I.N.R. Dubna Report No. P7-4124, (1968).
26. Peacock, N. J., Speer, R. J., and Hobby, M. G., *J. Phys. B.,* (Proc. Phys. Soc.) **2,** 798, (1969).
27. Oak Ridge National Laboratory, Thermonuclear Division Semi-annual Progress Report, ORNL 4150, April, 1967.
28. Peacock, N. J. and Pease, R. S., Proceedings of this Conference, p. 508.
29. Tonon, G. and Rabeau, M., International Conference on Ion Sources, Saclay, June 1969.
30. Daugherty, J. D., Eninger, J. E., Janes, G. S., and Levy, R. H., Proceedings of this Conference, p. 515.
31. Alvarez, L. W., *Phys. Rev.,* **58,** 192, (1940).
32. Walker, D., Fremlin, J. H., Link, W. T., and Stephens, K. G., *Brit. J. Appl. Phys.,* **5,** **5,** 157, (1954).
33. Ah-Hot, L., Baron, E., Bourgarel, M. P., Bieth, C., Cabrespine, A., and Goldstein, C., Proceedings of this Conference, p. 638.