On the generation and injection of heavy-ions into cyclotrons

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ABSTRACT

Passing an energetic ion beam through a gas or foil target produces ions of only a few charge states closely grouped about a mean value. The radius of curvature in a magnetic field of an ion at the mean charge is a constant, independent of the ion energy.

The interrelationships of the specific ionisation in gases and foils with regard to kinetic energy, magnetic rigidity, and cyclotron frequency are discussed with their consequences for injection into a cyclotron. Using a gas or foil stripper to start the acceleration process in a cyclotron results in a fixed energy gain for each type of ion due to the *Br* dependence.

Proposed designs of heavy-ion sources employing the advantages of the constant *Br* are presented. Ions of all elements, nitrogen through uranium, can be accelerated and stripped of a third to a half of their electrons while being accelerated to energies of over 1 MeV per nucleon.

One ion source employs a sectored ring magnet (edge focusing) with a static magnetic field adjustable to a *Br* of 1300 kG cm. In an acceleration ring chamber with a vacuum of 10^{-3} torr, the gas maintains the ion in a charge equilibrium state. A fixed frequency cavity type acceleration gap is used. The acceleration is by the stochastic process with the noise produced by the random change in charge.

A second proposed source uses a microtron type magnet. The operation is the inverse of the microtron in that the orbital period of each ion charge state is a multiple of that of a pulsed accelerating voltage. A stripping target at the acceleration gap maintains the ion in a charge equilibrium state.

1. INTRODUCTION

Current high interest in the investigation of predicted islands of stable elements at ^{114}Z and ^{126}Z has resulted in a number of proposals to combine a source of highly stripped heavy ions with injection into a cyclotron, in which the energy

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of the ions would be raised above the Coulomb barrier for the reaction under study.

The work presented in this paper originated from an investigation to determine the best combination of a Van de Graaff and a cyclotron for the production of high energy heavy ions. Attempts to couple the Van de Graaff to the cyclotron indicated that different combinations did not result in full freedom of choice. Studies of the production process of ion-atom interaction showed that only a few charge states about a mean value are produced; the mean value is linear with the ion velocity. The velocity-to-charge dependence for any given element sets a constant value of magnetic rigidity (Br) for the ions, independent of their velocity (energy).

Thus, all charge states of an ion produced by ion-atom interaction will rotate in a narrow band of radii within a magnetic field. Various methods of combining acceleration and stripping were studied and resulted in proposals for various methods of employing this nearly constant Br for the production of highly stripped heavy ions.

2. ION-ATOM STRIPPING

Currently the most direct method of producing multiply-charged ions is by passing energetic ions through a gas or foil target, since once an ion has been created and accelerated to any given velocity it is a simple matter to pass it through a gas or foil having sufficient cross-section (10^{16} atoms/cm^2) so that the ion will come to a mean charge equilibrium consistent with that velocity.

Experiments at HVEC[1] gave data showing that the mean ionisation state ($\bar{Q}$) of any heavy ion of (Z) nuclear charges is proportional to its velocity (V). For values of $\bar{Q} > 0{\cdot}3Z$ Dmitriev and Nikolaev[2] derived:

$$\bar{Q} = \text{constant } Z^{1/2}\, V \times 10^{-8} \text{ (charge, cm/s)} \qquad \ldots (1)$$

At velocities wherein Eqn (1) holds, no relativistic correction to mass is required. The velocity (V) of any ion of atomic mass (A) which has kinetic energy (T) is:

$$V = 1{\cdot}39 \times 10^{9} \left(\frac{T}{A}\right)^{1/2} \text{ (cm/s, MeV)} \qquad \ldots (2)$$

The mean charge, as a function of kinetic energy is:

$$\bar{Q} = C\left(\frac{2Z}{A}\right)^{1/2} T^{1/2} \text{ (charge, MeV)} \qquad \ldots (3)$$

The constant (C) depends upon the composition of the target, being 1·7 to 2·1 for various gas targets and 2·8 to 3·5 for various foil (solid) targets. For the very heavy ions above argon the relation should hold; for the lighter elements the value will vary slightly because the shell factor is more dominant, and individual calculations or experiments will be required to find the proper value of C.

To obtain numerical data for investigation of heavy ions a computer code was written, based upon the premise that when a heavy ion and an atom collide there will be an exchange of electrons. Whether the ion will pick up or lose another electron on each encounter with an atom depends upon the probability of the relative position and velocity of all the electrons of the ion and outer shell of the atom. Typical output data for ^{127}I in a gas target is plotted in Fig. 1.

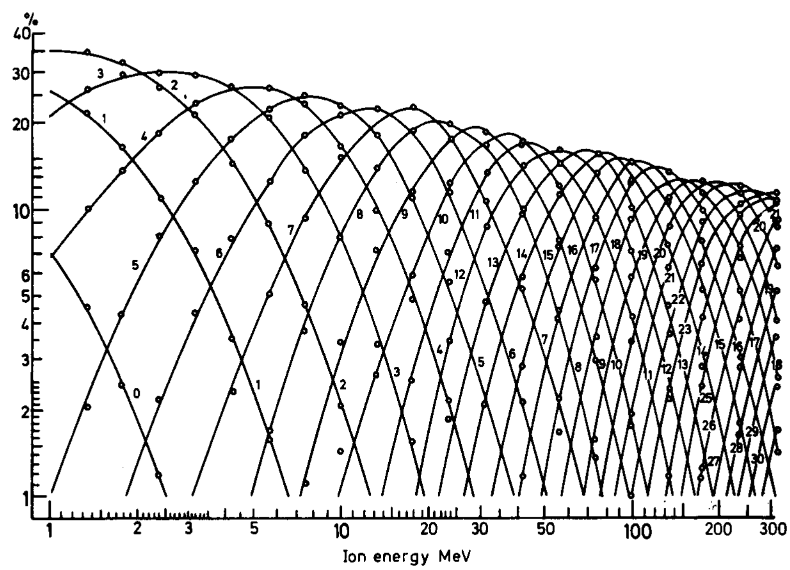

Fig. 1. Equilibrium charge state fraction for iodine ions in a typical gas target. Output data of computer code for random charge and distance between charges. (UM cyc. code: KDJ QQRAN*)*

3. MAGNETIC RIGIDITY

When injecting an ionised atom into the magnetic field of a cyclotron, the radius of curvature is the most important factor.

$$Br = 144\frac{(TA)^{1/2}}{Q} \quad \text{(kG cm, MeV, atomic mass)} \qquad \ldots(4)$$

Should the ion energy (T) and charge (Q) be independent variables, the magnetic field (B) and radius of curvature (r) could be independently selected. Substituting for the charge (Q) the mean charge state ($\bar{Q}$) of Eqn (3), Eqn (4) becomes:

$$Br = \frac{100\,A}{C\,Z^{1/2}} \quad \text{(kG, cm)} \qquad \ldots(5)$$

Thus at charge states $\bar{Q} < 0{\cdot}3Z$, the magnetic rigidity of an ion of mean charge is a constant, independent of velocity and energy. The ions do not have the mean charge $\bar{Q}$, but integral values near the mean form a group of charge states with a mean deviation equal to 0·85 times the square root of $\bar{Q}$.

In a cyclotron, the Br at extraction determines the output energy of the cyclotron.

$$T = 48\,\frac{(Br\,Q)^2}{A} \times 10^{-6} \quad \text{(MeV, kG, cm)} \qquad \ldots(6)$$

If an energetic ion beam is injected into the cyclotron and stripped by a foil near the centre, the foil must then be at a radius determined by the energy of the input ion beam. Thus:

$$\begin{array}{c}\text{CYCLOTRON OUTPUT}\\ \text{ENERGY}\end{array} = \begin{array}{c}\text{INPUT ION}\\ \text{ENERGY}\end{array}\left(\frac{Br \text{ input ion}}{Br \text{ max cyc}}\right)^2 \qquad \ldots(7)$$

Predicted values of Br for various ions are given in Table 1. The Br maximum of the UM cyclotron is 2200 kG cm.

Table 1. PROJECTED VALUES OF MEAN Br FOR ION-ATOM STRIPPING (kG cm)

Target	N^7_{14}	A^{18}_{40}	Kr^{36}_{84}	I^{53}_{127}	U^{92}_{238}
Foil	140	270	430	540	760
Gas	210	470	740	910	1300

The constant Br of an ion places a severe restriction on the method involving injection of an energetic low charge ion beam across the field through a foil where the ion is stripped to a high charge. To accommodate a variety of ion energies, the stripping foil must be adjustable in radius and azimuth, on account of Br dependence and the tangency of the input and circular orbit respectively.

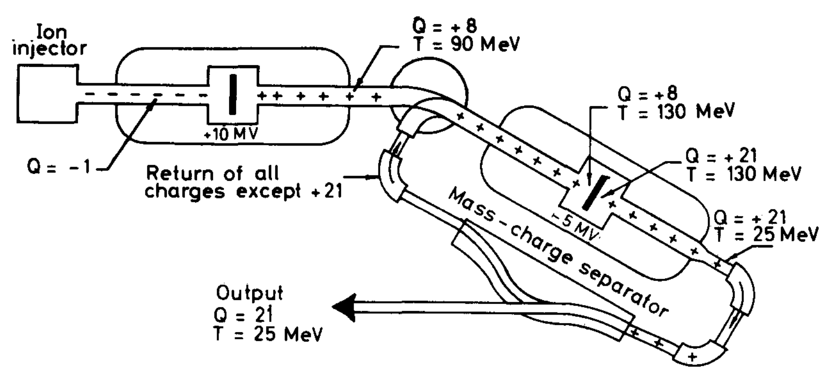

Fig. 2. Dual tandem Van de Graaff accelerators to accelerate ions to an energy value to strip them to a high charge then decelerate the ion beam. Adjusting the respective voltages of the positive and negative terminals will allow selection of both the charge state and the ion energy

The mechanical problems of foil replacement and accessible space could make this method difficult.

An alternative procedure is to produce an ion beam of the required charge state ($^+35$ to $^+45$ for Uranium) external to the cyclotron and inject the beam either axially or radially cycloiding between two electric plates. If the beam is produced by passing an energetic beam through a foil, the high charge state so produced facilitates decelerating the beam. Further, once the beam has been slowed down, rather weak electric and/or magnetic optics can control it. Fig. 2 shows a method using two tandem Van de Graaffs to produce a monoenergetic single charge state ion beam of which both the charge state and momentum can be independently controlled.

4. FREQUENCY

An ion beam will be accelerated by a periodic voltage of a frequency (f) and its harmonics.

$$f = 1{\cdot}53\, B_{kg}\, Q/A \quad (\text{MHz, kG}) \qquad \ldots (8)$$

At lower harmonically related frequencies (subharmonics), the beam would average an equal value of accelerations and decelerations if the accelerating voltage were sinusoidal. If the accelerating gap were pulsed at a frequency appropriate to Q equal to one, then all charge states would be accelerated up to a value at which the orbital period equalled twice the pulse width. For an ion beam of U_{238} and an 18 kG field, a 116 kHz accelerating pulse 100 ns wide would accelerate all charge states from U^{+1} to U^{+43}.

5. STRIPPING HEAVY ION SOURCES

Utilisation of the properties of ion-atom stripping suggests several conceivable methods of constructing an ion source in which it would be possible to strip as many charges as desired from any ion. The most significant of these properties is the relatively constant Br when stripping takes place under equilibrium conditions. It therefore follows that the ion source can be of reasonable size; nor need it have a centre, since the ion beam at all energies will be rotating in a doughnut-like ring.

5.1. *Stochastic heavy-ion source*

One such source is shown in Fig. 3, the main elements of which are four separated sector magnets with a mean radius of 100 cm and width of 50 cm. The magnet would use dominant radial focusing. The vacuum chamber would be filled with gas at a pressure at which the ions exchange one electron with a gas atom every one to five centimetres; thus each ion would have a mean charge about the equilibrium value as indicated by Eqn (3). Both the path length and the period of revolution would vary in a random manner. A special computer code using random numbers was employed to test the stability of the orbits. The orbits proved to be stable whenever a large number of collisions were used or a small amount of radial magnetic gradient was added. The edge angle of the sector magnet gives a form of radial stability—not by focusing, as normally used in analysing the field in a zero gradient synchrotron, but because the path length in the magnet is a function of radius. As there is no harmonic radial focusing term for the ion beam, there are also no resonances. Any radial resonance can be thought of as being gas damped. No tests were made for vertical focusing, but edge focusing should supply the needed vertical

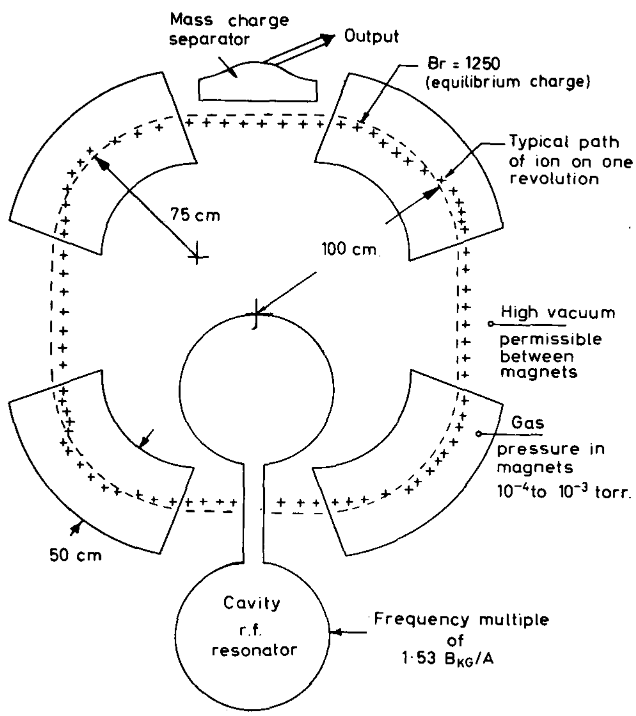

Fig. 3. Proposed heavy-ion source by accelerating ions in an equilibrium charge exchange gas atmosphere

focusing. The vertical focusing will be more like that of a quadrupole with one focusing edge, a space, a defocusing edge, and another space. Again the problem of resonances would be reduced by gas damping. The problem of over-focusing could be as much a problem as under-focusing.

As the period of ion rotation is random, a sine wave acceleration voltage will not be resonant to any orbital frequency but acceleration will take place on a stochastic basis, with each ion picking up and losing energy in a random manner. Some of the ions will reach sufficient energy and have sufficient charge to produce a useful beam of several microamperes. Due to the physical size of the ion source, the rotating ion cloud will be in the ampere range; thus very few ions need reach the necessary extraction energy.

A computer code was tried to test what percentage of iodine ions would be accelerated from a charge state of one, crossing a gap of 100 kV, and then being accelerated to an energy of 100 MeV. Some sets of random numbers gave results which seemed too optimistic; others gave believable results, while others gave no results. The problem is that random numbers generated by a computer are not truly random. The numbers in Table 2 are representative of the output after the handling of random numbers had been learned.

In general, only one ion in 200 reached 100 MeV; the remainder decelerated to zero energy. Those ions which accelerated to 100 MeV averaged 4000 revolutions, the ones which decelerated to zero averaged 200 revolutions each.

The frequency is not fixed as the acceleration is by the noise which is created by the variational path length caused by the changing charges. One output of the orbit computer code was the deviation from the mean path; the mean deviation averaged only 1% on most runs. This orbit code did not take into account the deviation from integral charge; thus the path length deviated 1% from that of the mean ionisation charge of Eqn (3), which is non-integral. Therefore, if the energy is random the period would also be random, thus resulting in pure noise for acceleration. Notwithstanding the foregoing, it is believed prudent for the period of the accelerating voltage to be shorter than the revolutionary period of the most energetic ion. A good choice of frequency is that of the accelerator into which the ions are to be injected.

Proof of the operation of such an ion source can be demonstrated on almost any cyclotron. If a probe is inserted slowly during the initial pumping period immediately after a shut down (with the magnet and rf on and ion source off), no spill beam will be measured on the probe until, at a radius at which the *Br* equals 200 kG cm, a small beam will appear and be present for several cm. It will be independent of rf, but its radius will vary linearly with changes in the magnetic field. This beam the author believes to be nitrogen ion in charge states

Table 2. COMPUTER OUTPUT FOR STOCHASTIC ACCELERATION OF IODINE ION USING RANDOM PHASE AND CHARGE

Exit ion	*Total cycles*	*Dumps at zero*	*Cycles to exit*	*Charge at exit*	*Exit Energy* MeV
1	13003	26	4786	16	100·27390
2	22348	15	3745	22	100·63156
3	58224	52	7170	12	100·15144
4	132774	123	10587	21	101·33485
5	141200	22	3629	19	100·29720
6	230509	255	4003	20	100·17560
7	235811	16	2548	16	100·39693
8	323335	165	3413	14	100·68129
9	349912	90	1118	18	101·16209
10	400807	204	2174	18	100·67841
11	474483	259	4355	19	101·00648
12	530715	275	6426	28	101·30888
13	548288	105	4002	23	100·39429
14	554884	51	3438	23	100·61908
15	601176	256	6921	19	101·45299
16	756099	1315	2218	18	100·24274
17	772039	166	3590	21	101·71747
18	780816	57	2076	16	100·02669
Total	780816	3450	76196	343	1812·55179
Average	43378	192	4233	19	100·69732

from +1 to +5. If argon gas were to be introduced into a clean cyclotron, the same phenomenon ought to appear but at a value of *Br* of 400 kG cm. The gas pressure localised at the radius of the ion ring should be 10^{-3} torr, which would be the case with the majority of cyclotrons when the normal tank reading is near 10^{-4} torr. In the start-up of the University of Maryland cyclotron, hindsight indicates that such a phenomenon was indeed observed: but as this present theory had not been developed at that time, no experiments were made to positively identify the ions.

5.2. *Inverted microtron heavy-ion sources*

Another such ion source, Fig. 4, would have a pulsed accelerating gap with a stripping target located just before the accelerating gap. Using a pulse rate set for a charge of one, all the ions will return to the accelerating gap one or more times in synchronisation with the accelerating pulse. Each time, the ion will

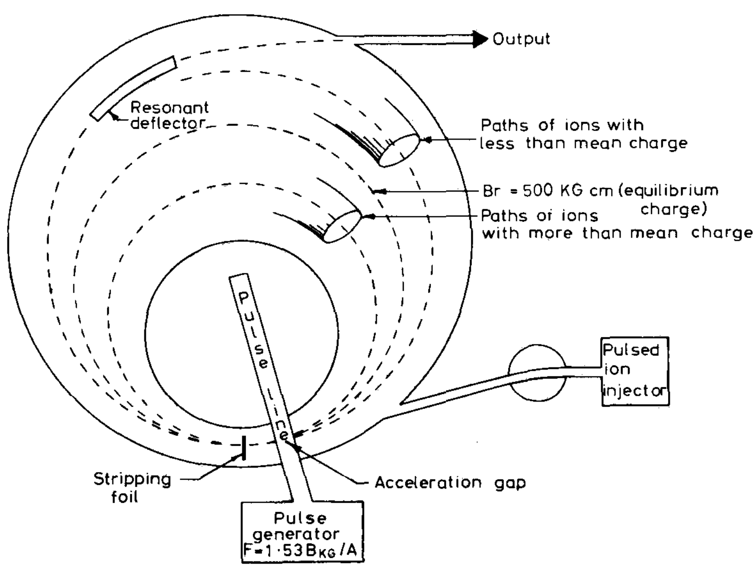

Fig. 4. Proposed heavy-ion source wherein multicharged ions are accelerated in a magnetic field. The periods of rotation of all ion charges are multiples of the pulsed accelerating voltage

take on a random charge state on passing through the target but will remain in resonance. As the ions pick up energy, they will be stripped to higher and higher charge states; but the mean radius will remain constant until the charge state becomes greater than $0{\cdot}3Z$, at which time the radius will begin to increase. The orbits of different charge states will have maximum separation 180° from the stripping target and be focused at the stripping target. From Eqn (6) we see that a number of ions are to be found at any specified diameter, that is all ions with the same value of $T^{1/2}/Q$. For any given energy, the higher charge states arrive at different times in respect to the accelerating pulse, as shown in Table 3.

A phased pulsed deflector can separate out the specific charge and energy state. The ion will make a number of revolutions equal to the charge

Table 3. CHARGE, ENERGY, AND PERIOD OF U_{238} AT 18 kG AND 150 cm DIAMETER

Q	20	21	22	23	24	25	26	27	28	29	30
MeV	145	162	178	194	212	230	248	267	287	309	331
ns	416	396	378	362	348	333	320	308	298	287	278

state before the energy is increased by the next accelerating pulse. On each revolution the charge state will vary in a random manner; thus the ions at the chosen energy will be extracted on that revolution at which they attain the preselected charge state. All ions will be extracted at one chosen energy and one chosen charge and with a microscopic duty cycle equal to that of the high charge state. If the frequency and field parameters are selected to match the second stage of the 'Rickey' sectored cyclotron, with its input radius of 100 cm and exit of 300 cm, the final energy will increase by a factor of 9.

A major problem in the construction of such an ion source would be the pulsed accelerating voltage, although a proper combination of harmonically related sine waves may produce proper acceleration. The vacuum must be very high, as gas in the accelerating chamber will cause a change in ionisation at a point other than the stripping target. Adding or subtracting charges must take place only at the stripping target in order for the ion beam to remain focused and ordered.

6. CONCLUSION

The most significant data resulting from this study is that obtaining highly charged ions by means of ion-atom interaction would produce heavy ions with charge states for which the magnetic rigidity (*Br*) is nearly constant for charges from 1 to 0·3 times the atomic number. This constant *Br* would permit construction of a heavy ion source of reasonable dimensions and cost, which should accelerate and strip as many as 50% of the total electrons from any atom convertible into a gaseous state.

DISCUSSION

Speaker addressed: K. D. Jenkins (Maryland)

Question by J. R. J. Bennett (RHEL): Will you give your estimate of current and energy from your device for say uranium particles.

Answer: If the chamber is filled with uranium gas, the gas will be ionised and be equivalent to many amperes due to the large number of atoms (10^{20}). If an estimate is made that only 0·1% of accelerated ions are not lost to scattering and 0·5% of ions are accelerated to 100 MeV then the expected current would be in the μA range. The energy limit is dependent upon when the ion charge does not follow a linear velocity dependence. Thus uranium would be accelerated in the enclosure to about an energy of 1000 MeV.

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