Design Considerations for a Possible Heavy Ion Accelerator at A.E.R.E.

Introduction

Accelerator requirements for chemical studies at A.E.R.E. have been set out in two recent papers [1,2]. Briefly these are: a) Intense extracted beams of ions of as many elements as possible, with energy controllable up to 12 MeV/nucleon for the lighter ions; such beams should be virtually continuous, fluctuations at frequencies of the order of 1 kc/s or less are unacceptable. The energy spectrum of the beam should not exceed a few percent in width. b) An intense proton beam (about 100 μA) of energy of at least 50 MeV, preferably 100 MeV. The only machine which can provide continuous beams of the required intensity is a continuous (as opposed to a 'frequency modulated') cyclotron. Although up to the present no single cyclotron incorporating all these features has been made, it now appears possible that this could be done.

Design Requirements

Before considering in detail what new machine might be designed for this work, it will be well to consider what has been already achieved. Several heavy ion machines of similar size are in existence; as an example we may take the 'Crocker' machine at the University of California. This has a 300 ton magnet with 60" diameter poles, and consumes not more that 500 kW of power (the Harwell cyclotron also consumes 500 kW). It accelerates protons, deuterons, α-particles and C^{6+} ions to 10 MeV/nucleon, and heavier ions (with charge to mass ratio less than that of the deuteron) to lower energies. Currents are roughly as follows [3]

	W/nucleon	Internal current. μa	External current. μA.
^{1}H	10	300	40
^{2}H	10	500	75
^{4}He	10	300	60
^{13}C	7 - 9	0.1	3.10^{-6}
^{14}C	7 - 9	0.05	10^{-6}
^{14}N	6.5 - 10	0.05	-

In this machine the energy of the extracted beam is not variable, though the energy of the beam impinging on an internal target can be varied simply by moving the target radially inside the machine. It falls short of the present requirement in this respect, and again because the maximum proton energy is 12 MeV, whereas we require 50 - 100 MeV.

The Crocker cyclotron is not adequate, so that we must see how it could be modified. First, we consider energy variation. The energy of a particle at the outer edge of the cyclotron is proportional to the square of the magnetic field, and since the field is proportional to accelerating frequency a decrease of four in energy necessitates a decrease of two in the magnetic field and in the accelerating frequency. Decreasing the magnet field is easy, but a change of a factor two in the accelerating frequency requires a complicated and sophisticated r.f. system. There are some low energy variable cyclotrons in which this frequency change can be made, but none as large as this. This then is a problem in which some development is required.

The second inadequacy of the Crocker machine is that protons can only be accelerated to 12 MeV. The limitation here is not the magnet, at full field it is capable of containing 50 MeV protons. The trouble is that the relativistic mass increase limits the available energy/nucleon in conventional constant frequency systems to about 12 MeV. This difficulty may be overcome by using a magnet with an azimuthally varying field. A suitable field could be provided by having three or four radial ridges on the poleface, with a field modulation [defined as $B_{max} - B_{min})/(B_{max} + B_{min})$] of about 0.45. This large modulation necessitates a high peak field in the iron or a large radius, since it is the mean field which determine the effective radius of curvature of the orbit. Spiralling the ridges enables the modulation to be reduced, but at the cost of some increase in complexity. The theory of spiral ridges is now well understood, and model experiments have been done. Indeed two models are under construction at A.E.R.E., and should be undergoing tests early next year. Figures for the degree of spiralling required in the present machine are given in Appendix 1. It should be noted that the radio frequency required for a given magnetic field is proportional to N/A, where N is the charge state and A the atomic mass number, and that to accelerate protons requires an <u>increase</u> in the accelerating frequency. If therefore variable energy for deuterons, and also the acceleration of protons are required a range of about four in frequency is required. This would be very difficult with a conventional dee system, and a form of harmonic operation would be required. For example a four dee system could be used. For normal operation adjacent pairs would be connected; for operation equivalent to that with half the frequency, opposite pairs would be connected. (See fig. 2). It is worth noting at this point that the use of spiral ridges removes entirely the energy limitation due to the relativistic mass increase.

Normally (as in the Crocker machine) the effect is minimized by the 'brute force' method of using a high dee voltage, so that the number of turns is small.

It would appear therefore that a machine with the same magnet size as the Crocker machine could be built to provide variable energy beams and to accelerate protons to 50 MeV if a variable frequency r.f. system can be designed, and if the magnet field can be varied in both strength and to some extent in shape. These problems can certainly be solved, but will require some considerable development effort. It may be that if an attempt is made to make the machine too versatile, it will become unreasonably complicated. These problems are being actively studied in the U.S.A. at the moment by several groups; in particular there is a group at Oak Ridge which is considering a machine with the following parameters:(4)

Pole diameter: 2 metres

Energy range of particles per nucleon:

$^{1}H^{+}$	$^{2}H^{+}$	$^{4}He^{++}$	$^{14}N^{4+}$
1 - 75	$\frac{1}{2}$ - 19	$\frac{1}{4}$ - 19	$\frac{1}{4}$ - 7

Azimuthal variation of field 7 kg - 16 kg (max)

Dee to ground volts: 100 kV

Power 1½ MW (?)

Cost (including building) $ 3 M

Much study has gone into this, and magnet models have been made. Nevertheless much remains to be done before the magnitude of the project can be fully assessed.

<u>Proposal</u>

We would tentatively suggest a machine slightly less ambitious than the Oak Ridge proposal for study; below are some parameters:-

Pole diameter 60".

Frequency variation:

6 - 10 mc/s, 20 mc/s (for protons).

This frequency range will allow the following energies/nucleon to be achieved at the outer edge of the machine:

Protons (N/A = 1) : 50 MeV, 4 - 12 MeV.

Deuterons, α particles (N/A = 0.5) : 4 - 12 MeV.

Ions with N/A = 0.4 : ~~7 - 12~~ 4-7 MeV

Ions with N/A = 0.3: 4 MeV.

Ions with N/A < 0.3: less than 1 MeV (accelerated by harmonics of the radio frequency)

Magnet weight (total) 300 tons.

Power (total) ½ megawatt.

This seems a 'reasonable' machine. As a result of further study we may find that we can do better, or if things turn out badly, not so well. It is difficult to prophesy intensities, but these should certainly be at least those of existing machines.

Staff, cost and timescale

Very roughly we estimate a group of 20 scientists and research engineers (including at least two chemists) plus additional professional engineers. We should try to plan the project in a similar way to the 7 GeV machine, but on a smaller scale, making use of Industrial Group services, certainly for progress and inspection in Industry and possibly for supervision of civil and mechanical and electrical contractors.

The cost, including buildings, should be of the order of £1 M, and the construction time 3 - 4 years from the approval date. These figures will of course depend on the final choice of machine; if greater energy variation is required as in the Oak Ridge proposal the development time will be longer and more physicists will be needed; if on the other hand the need to accelerate protons were dispensed with this would require much less development, it would save possibly up to a year in the timescale and a quarter of the cost, and would need fewer high grade physicists. The number of professional engineers would probably show less difference.

In conclusion two additional arguments in favour of this project may be cited. First, it will further advance the art of machine design along lines in which the accelerator division is already working, bringing nearer the day when high energy continuous cyclotrons become feasible, and secondly it will provide a proton beam of high intensity which will also be of considerable interest to nuclear physicists.

21st November, 1958.

References

1. A proposal for a low-energy cyclotron on the Harwell Site. W. Wild September 30th 1958.
2. Use of Accelerating machines in Fission chemistry group. G.N. Walton.
3. U.C.R.L. 2513, Quarterly Progress report. 1954.
4. A preliminary description of the proposed Oak Ridge general accelerator ORNL CF58-7-62. August 1958.

Appendix 1

Fundamental relationships

Equating the centrifugal to the Lorentz force on an ion in a magnetic field yields

$$\frac{Amv^2}{R} = \frac{NevB}{c} \qquad \text{........ 1}$$

where m = protons mass

A = atomic mass number

B = magnetic field

v = particle velocity

N = charge state

for a fixed magnetic field, we have therefore, where the subscript p refers to protons

$$\frac{v}{v_p} = \frac{N}{A} = \frac{\omega}{\omega_p} \qquad (\omega = \text{angular velocity})$$

$$\frac{T}{T_p} = \frac{N^2}{A} \qquad (T = \text{kinetic energy})$$

$$\frac{T/\text{nucleon}}{T_p} = \frac{N^2}{A^2}$$

For a fixed frequency machine on the other hand

$$\frac{v}{v_p} = 1 = \frac{T/\text{nucleon}}{T_p}$$

$$\frac{T}{T_p} = N$$

$$\frac{B}{B_p} = \frac{A}{N}$$

Let us consider a cyclotron with a maximum usable radius of 30". From equation 1 the kinetic energy of a proton at this radius for a field of 14 kg (a reasonable value) is 54 MeV. On the basis of these results a table may be drawn up for energies available either in a fixed field with variable frequency (difficult) or a fixed frequency with variable field (easy). The advantage of the former will be immediately evident, since in a fixed frequency machine the proton energy is severely limited, and ions with N/A much less than ½ cannot be accelerated at all. In the Crocker machine a small variation of frequency ($\ll 2:1$) is possible.

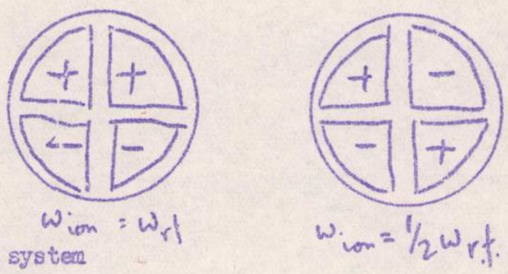
Element		A	^{1}H	^{2}H	^{3}He	^{4}He	^{9}Be	^{12}C	^{12}C	^{14}N	^{14}N	^{20}Ne	^{20}Ne	^{40}A	^{40}A
Charge state		N	1	1	2	2	4	3	6	4	7	5	10	10	18
For a fixed magnetic field of 14 kg radius 30"	Kinetic Energy	$\frac{54N^2}{A}$	54	27	72	54	97	41	162	62	190	67	270	135	430
	KE/nucleon	$\frac{54N^2}{A^2}$	54	13	18	13	11	3	13	4	13	3	13	3	11
	Frequency mc/s	$\frac{20N}{A}$	20	10	13	10	9	5	10	6	10	5	10	5	9
For a fixed frequency of 10 mc/s, radius 30"	Kinetic Energy	$\frac{54N}{4}$	13	27	41	54	(123)	-	162	-	190	-	270	-	(540)
	KE/nucleon	$\frac{54}{4}$	13	13	13	13	(13)	-	13	-	13	-	13	-	(13)
	Magnetic field, K-gauss	$\frac{7A}{N}$	7	14	11	14	16	28	14	25	14	28	14	28	16

Table showing energies obtainable in a radius 30" cyclotron with 14 kg mean field. The greater versatility of variable frequency operation is shown. Bracketed figures require a magnetic field which is higher than normal. Where an impossibly high field is required no energy values are shown.

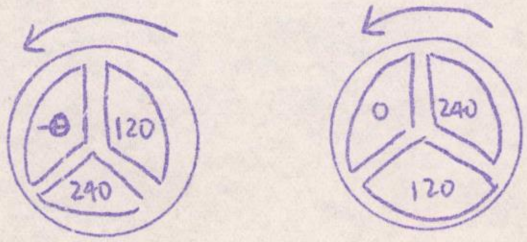
Harmonic Operation

Dee systems allowing the values of angular velocity with the same applied radio frequency are shown

a) 4 dee system



b) 3 dee system



Appendix 2

Ridge parameters

In order to obtain vertical focusing Q_v must exceed zero; from the standard 'smooth approximation' formula we have for a constant frequency field low.

$$Q_v^2 = -k + \delta^2 (\cot^2\sigma + \tfrac{1}{2}) \qquad (2)$$

where Q_v = free oscillation frequency/angular rotation frequency

$k = \frac{r}{B}\frac{dB}{dr}$

$\delta = (B_{max} - B_{min}) / (B_{max} + B_{min})$

σ = angle between spiral ridge and circumference

Also for β ($= v/c$) small, $k \approx \beta^2$ whence from equation 2 with $Q_v > 0$

$$\delta > \beta/(\cot^2\sigma + \tfrac{1}{2}) \qquad (3)$$

Now at 54 MeV β for protons = .32, and at 27 MeV β for deuterons = .16, so for the machine previously considered (30" radius, B = 14 kg) we have

σ	δ_{min} protons	δ_{min} deuterons
30°	.17	.08
45°	.26	.13
60°	.34	.17
90°	.45	.22

$\sigma = 35°$, $\delta = .2$ seems a reasonable choice, with N = 3 ridges. The Oak ridge group plan a profile as shown in Fig. 1 (for 75 MeV)

B varies from 7 to 16 kg

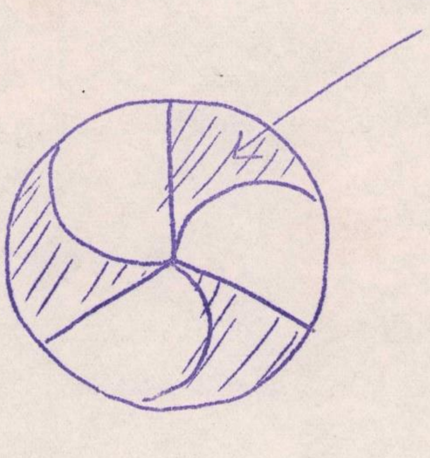


Fig. 1