Conceptual design of a two-stage, two-gap cyclotron*

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ABSTRACT

The two-stage, two-gap cyclotron which is described has the following features related to the acceleration of heavy ions: (1) Isochronisation of all orbits is possible, (2) the radiofrequency may be at or near the optimum harmonic of the ion frequency in each stage, (3) one stripping process is used and the stripping foil is external to the cyclotron and, (4) a minimum of 9 MeV/amu is obtained after two stages of acceleration. The maximum potential required of the preinjector is 700 keV. The machine also produces 200 MeV protons, 240 MeV deuterons, 170 MeV tritons, and corresponding energies of other light ions. For these a small syclotron is used to pre-accelerate the ions prior to injection into the second stage.

1. INTRODUCTION

Dzhelopov *et al.*[1] have presented the conceptual design for a two-stage cyclotron which is capable of accelerating heavy ions from ~0·1 MeV/amu to ~7 MeV/amu. After a first acceleration and extraction ions are returned to the centre of the cyclotron where, upon passage through a stripping foil, the charge state is increased by a factor of three. A second acceleration and extraction follows. The design is based on a suggestion of Tobias.[2] Because of the difference of the importance of the relativistic effects in the two acceleration stages, making the magnetic field radial profile the same for both stages entails considerable loss in phase. The present paper deals with the conceptual design of a two-stage cyclotron in which successive accelerations take place in two separate magnet gaps which share the same magnetic return path. Several desirable features are thereby obtained. These and other features of the design appear under Discussion.

2. CYCLOTRON DESIGN AND PERFORMANCE

The cyclotron magnet has four radial sectors.[3] The principal design parameters are listed in Table 1. Note that the two magnet gaps are spaced 38·1 cm between

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Table 1. DESIGN PARAMETERS

Vertical separation of the stages is 38·1 cm	Stage one	Stage two
Number magnet sectors; angle; spiral	4; 45°; 0	4; 45°; 0
Radius of curvature at injection (m)	0·385	0·470
Maximum distance of orbit to centre at injection (m)	0·770	0·940
Radius of curvature at extraction (m)	1·88	1·88
Maximum distance of orbit to centre at extraction (m)	3·76	3·76
Magnet gap (cm); maximum field (kG); energy multiplier	7·6; 17·5; 23·8	7·6; 17·5; 16
Charge on heavy ions	+Q	+4Q
Number of dees; dee width	2; 30°	2; 30°
Frequency range (MHz); harmonic range	2·7–5·8; 6–9	11–23; 6–9
Dee voltage, centre (kV); dee voltage, final orbit (kV)	150; 160	150; 200
Injection	Magnetic	Magnetic + Electrostatic
Extraction	Electrostatic	Electrostatic

centrelines. The pole piece between gaps is 30·5 cm thick.

The non-relativistic approximation for the final energy of an ion is $E = 513\, q^2/A$ MeV.

The magnetic fields in the two gaps will be very nearly equal. Since the charge state is increased by a factor of four by stripping between stages, the particle frequency in the second stage will be four times that of the first stage.

The design of the machine places severe requirements on the vacuum. Cryogenic techniques have been found convenient in high vacuum cases and will be required here.

The performance characteristics appear in Table 2. For elements heavier than sulphur, the ions are pre-accelerated by a 700 keV Cockroft-Walton and then injected into the first stage of the two-tier cyclotron. After acceleration, extraction and stripping they are returned to the centre of the second stage and further accelerated.

For ions lighter than sulphur, pre-acceleration takes place in a small cyclotron and the ions are injected directly into the second stage of the two-tier cyclotron.

3. DISCUSSION

The provision of a separate magnet gap for each stage of the acceleration leads to the following desirable features.

(1) Although the magnetic fields in the two gaps are almost uniform and equal, small adjustments in the radial profile through the use of trim coils may be used to isochronise the orbits of each stage.

(2) An individual rf system may be used for each stage. Thus, the rf may be at or near the optimum harmonic of the ion frequency in each of the stages.

Note that the stripping foil may be located outside the cyclotron. Due to the limited lifetime of these foils, this is a much more favourable location than one inside the machine. The location outside the cyclotron is achieved by increasing the charge by a factor of four on stripping and having a factor of four as the

Table 2. PERFORMANCE CHARACTERISTICS

	Second stage + Small cyclotron								Two-stage cyclotron			
Element	H	H	H	He	He	Li	C	Ne	S	Br	I	U
Z	1	1	1	2	2	3	6	10	16	35	53	92
A	1	2	3	3	4	6	12	20	32	80	127	238
Maximum energy MeV	200	240	170	630	480	720	680	640	800	1335	1870	2130
Maximum energy MeV/amu	200	120	57	210	120	120	57	32	25	16·7	14·7	9·0
Second stage injection energy–MeV (from small cyclotron)	9·1	12·6	10·4	28·5	25·2	37·8	41·4	40·0				
Second stage injection energy–MeV (from first stage)									50·1	83·4	117	134
Ion charge (first stage)									3	5	7	8
Ion charge (second stage)	1	1	1	2	2	3	4	5	12	20	28	32
Turn spacing at final radius–mm (second stage) 200 kV dee to ground	5·3	4·5	6·3	3·4	4·5	4·5	6·3	8·3	22	22	22	22
Number of turns (second stage) 175 kV dee to ground (average)	405	486	346	637	486	486	346	259	96	96	96	96
Harmonic in use (30° dees)	3	3	3	3	3	3	3	3	6	6	6	6

ratio of final orbit length of the first stage to the injection orbit length of the second stage.

Fig. 1 shows that at the inter-stage energy, i.e. the stripping energy, for formvar the mean ionic charge on stripping[4] is never more than two units from the charge required for acceleration in the second stage. Consider the *U* curve. The bars perpendicular to the curve indicate the maximum final energy corresponding to various charge states. For acceleration to final energies between approximately 1200 and 1600 MeV, a charge state of 28 would be used after stripping. The curve indicates that the mean charge produced at the corresponding inter-stage

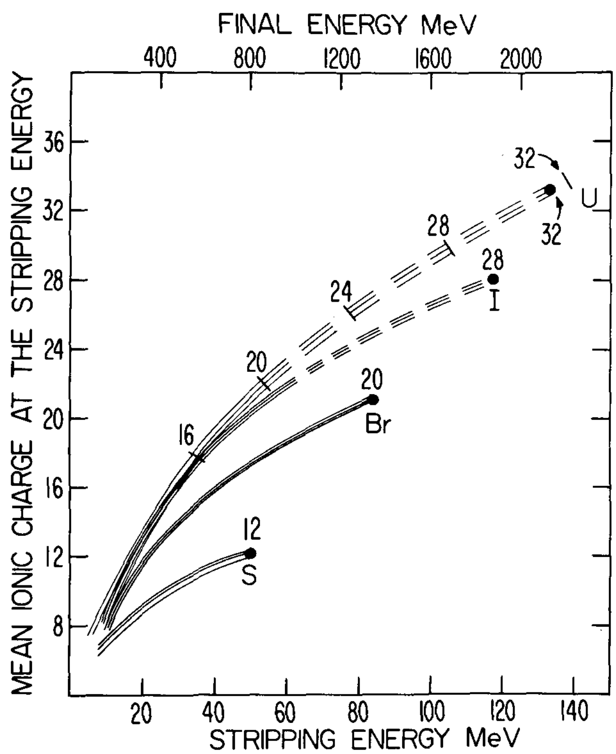

Fig. 1. The mean ionic charge produced by formvar vs the stripping energy for several ions. For U *the bars indicate the maximum final energy obtainable with various second-stage charge states. The dots indicate the maximum final energy obtainable with a preinjection potential of 700 kV*

stripping energies would range between 26 and 30. If one remains within two charge units of the mean charge, the loss of intensity at stripping is no more than twice the minimum loss.[5] Such is the case for the range of operation indicated by the curves in Fig. 1.

The change of charge state by a factor of four, together with the overall design (the energy multiplier of the first stage is 23·8 and of the second is 16) allows one to accelerate heavy ions to a minimum of 9 MeV/amu with (1) only one stripping process and (2) the use of a preinjection unit (Cockcroft-Walton) whose maximum potential is 700 kV. The solid dots in Fig. 1 indicate final energies corresponding to the indicated second-stage charge states and 700 kV preinjection potential. Higher charge states could be used, but the mean charge vs stripping energy characteristics begin to cause considerable loss of intensity.

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