Design specifications for compact cyclotrons

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ABSTRACT

Design specifications for compact cyclotrons have been examined from the point of view of their applications in the following fields.
(a) Radioisotope production
(b) Production of neutrons
(c) Activation analysis
(d) Radiation physics and radiation biology
(e) Injection into Tandems and low-energy nuclear physics.

The maximum energy, internal and external beam intensities, energy resolution, beam quality, and energy and particle variability are fully discussed. Extensive tabulations of calculated isotope yields and neutron output as well as of theoretical detection sensitivities for charged-particle activation from cyclotrons of various sizes are presented.

It is suggested that the designers should aim at one standard size which should be a good compromise between the cost and scope of its applications. It should be offered in two versions:
(a) Fixed energy machine with no provision for accelerating heavier elements.
(b) Variable energy machine with added facility of external ion source for accelerating heavier elements and polarised particles.

1. INTRODUCTION

The main use of compact cyclotrons is likely to be in the medical, biological, and irradiation fields though they also offer the possibilities of enhancing the maximum energy of a Tandem Van de Graaff to useful regions,[1,2] and a relatively cheap facility for low-energy nuclear physics. In this paper, therefore, we shall be mainly concerned with the demands on the design specifications of a compact cyclotron laid down by its potential applications in the biomedical fields with special reference to isotope and neutron production and activation analysis. The requirements on the design from the points of view of injection into Tandems and low-energy nuclear physics will also be briefly mentioned at appropriate places.

The following points will be discussed in detail:
(1) Maximum attainable energy
(2) Internal and external beam intensities
(3) Beam quality and energy resolution
(4) Energy and particle variability

1. BEAM ENERGY

This is probably the most important parameter in designing a cyclotron as it determines the size, the cost, and the usefulness of the machine. Two years ago when compact cyclotrons first came on to the market the maximum deuteron energy was limited to 7·5 MeV to provide a relatively low cost installation capable of a limited range of isotope production and radiation. Machines are now available up to 11 MeV.

In low-energy nuclear physics and for injection into Tandems the maximum energy of a cyclotron is not so critical as in the case of isotope and neutron production. For production to be effective the cyclotron beam must have enough energy to overcome the Coulomb barrier and reaction thresholds even in the heaviest nuclides. With increasing energy the yields of isotopes and neutrons would continue to increase if a thick target were used, but the rate of increase would fall off with increasing energy. On the other hand the cost of a cyclotron would rise rapidly with the maximum energy. It seems, therefore, that there may be an optimum maximum energy beyond which the extra advantage gained in certain applications may not be economically justified.

We have carried out extensive calculations for isotope and neutron production and activation analysis with cyclotrons of different sizes which are represented by the maximum available deuteron energies of 8, 12, 16, and 20 MeV respectively. The corresponding proton and α-energies are taken to be twice the deuteron energy. It is estimated that the cost of a machine varies approximately as the cube of its radius which is in proportion to the energy to the power 3/2. The price of a cyclotron with a maximum deuteron energy of ~10–11 MeV has been quoted to be around \$300 000 to \$350 000 both by AEG and Philips.[3,4]

RESULTS AND DISCUSSION

Table 1 shows calculated thick-target isotope yields, neutron production and detection sensitivities of various elements in tissue-equivalent matrix through (p, n) reactions. The isotopic yields and detection sensitivities refer to saturation activities. A beam intensity of 1 μA has been used in the calculations. Empirically constructed excitation functions[5] have been used along with the available stopping-power data.[6]

It may be clearly seen from the tables that though the yields go on increasing with energy, the rate of increase drops off at higher energies. A similar pattern is observed in deuteron and α-induced reactions with one particle emission as shown in Tables 2, 3, 4, and 5.

Table 1. (p, n)

Maximum energy	16 MeV			24 MeV			32 MeV		
Z of the elements	20–40	41–60	61–83	20–40	41–60	61–83	20–40	41–60	61–83
Isotopic yield mCi/μA	273	117	2·4	359	160	2·9	383	171	3·1
Neutron yield n/s/μA	$1{\cdot}0 \times 10^{10}$	$4{\cdot}3 \times 10^{9}$	$9{\cdot}0 \times 10^{7}$	$1{\cdot}3 \times 10^{10}$	$5{\cdot}9 \times 10^{9}$	$1{\cdot}1 \times 10^{8}$	$1{\cdot}4 \times 10^{10}$	$6{\cdot}3 \times 10^{9}$	$1{\cdot}1 \times 10^{8}$
Detection sensitivity in oxygen matrix d.p.s./p.p.m./μA	$7{\cdot}0 \times 10^{3}$	$2{\cdot}8 \times 10^{3}$	$3{\cdot}8 \times 10^{2}$	$9{\cdot}5 \times 10^{3}$	$3{\cdot}8 \times 10^{3}$	$4{\cdot}9 \times 10^{2}$	$1{\cdot}0 \times 10^{4}$	$4{\cdot}0 \times 10^{3}$	$5{\cdot}2 \times 10^{2}$

Table 2. (d, n)

Maximum energy	8 MeV		12 MeV		16 MeV		20 MeV
Z of the elements	20–40	41–60	20–40	41–60	20–40	41–60	41–60
Isotopic yield mCi/μA	14·5	0·3	40·1	1·8	59	3·4	4·7
Neutron yield n/s/μA	$5{\cdot}4 \times 10^{8}$	$1{\cdot}2 \times 10^{7}$	$1{\cdot}5 \times 10^{9}$	$6{\cdot}7 \times 10^{7}$	$2{\cdot}2 \times 10^{9}$	$1{\cdot}3 \times 10^{8}$	$1{\cdot}8 \times 10^{8}$
Detection sensitivity in oxygen matrix d.p.s./p.p.m./μA	$7{\cdot}2 \times 10^{2}$	$3{\cdot}2 \times 10^{1}$	$1{\cdot}3 \times 10^{3}$	$1{\cdot}9 \times 10^{2}$	$1{\cdot}8 \times 10^{3}$	$3{\cdot}8 \times 10^{2}$	$5{\cdot}2 \times 10^{2}$

Table 3. (d, p)

Maximum energy	8 MeV			12 MeV			16 MeV			20 MeV		
Z of the elements	20–40	41–60	61–83	20–40	41–60	61–83	20–40	41–60	61–83	20–40	41–60	61–83
Isotopic yield mCi/μA	24·0	4·9	0·3	63·5	24·7	8·7	99·2	48·6	27·0	124·3	67·9	44·3
Detection sensitivity in oxygen matrix d.p.s./p.p.m./μA	4·1 × 10^{2}	9·2 × 10^{1}	10^{0}	1·4 × 10^{3}	4·7 × 10^{2}	1·4 × 10^{2}	2·2 × 10^{3}	9·5 × 10^{2}	4·5 × 10^{2}			1·2 × 10^{3}

Table 4. (α, n)

Maximum energy	16 MeV			24 MeV			32 Mev		
Z of the elements	20–40	41–60	61–83	20–40	41–60	61–83	20–40	41–60	61–83
Isotopic yield mCi/μA	3·6	0·8	0·04	20·5	6·6	1·7	27·1	8·2	2·4
Neutron yield n/s/μA	1·3 × 10^{8}	3 × 10^{7}	1·6 × 10^{6}	7·7 × 10^{8}	2·4 × 10^{8}	6·3 × 10^{7}	1·0 × 10^{9}	3·0 × 10^{8}	8·7 × 10^{7}
Detection sensitivity in oxygen matrix d.p.s./p.p.m./μA	8·8 × 10^{1}	1·3 × 10^{1}	7·8 × 10^{-1}	5·7 × 10^{2}	1·3 × 10^{2}	2·5 × 10^{1}	7·5 × 10^{2}	1·7 × 10^{2}	3·6 × 10^{1}

Table 5. (α, p)

Maximum energy	16 MeV		24 MeV		32 MeV	
Z of the elements	20–40	41–60	20–40	41–60	20–40	41–60
Isotopic yield mCi/μA	4·6	0·2	19·8	40·4	25·5	69·2
Detection sensitivity in oxygen matrix d.p.s./p.p.m./μA	1·0 × 10^2	3·0	4·8 × 10^2	7·8 × 10^1	6·2 × 10^2	1·4 × 10^2

Yields from p, d and α-induced reactions where two particles are emitted are shown in Tables 6, 7, and 8. It can be seen from these that the smallest machine either produces no yield or a poor yield in comparison with the bigger machines.

Reactions where three particles are coming out are dealt with in Tables 9 and 10. It is seen that even with 24 MeV protons and α-particles yields of isotopes attainable with these reactions are likely to be small.

The tables show that with increasing energy we not only get higher yields but also produce activities through emission of two or three particles which is an advantage. However, there are some disadvantages too of having higher energies. When producing activities through one-particle emission reactions, those generated simultaneously through multi-particle emission may give rise to other unwanted and troublesome activities.

Isotopic yields of some of the clinically interesting isotopes are summarised in Table 11 where experimentally measured excitation functions have been used.

Due to the lack of available data on ^{3}He-induced reactions we have not been able to include this projectile in our calculations. For a 12 MeV deuteron machine the maximum obtainable ^{3}He energy would be about 32 MeV.

Yields from some useful neutron-producing reactions have been given in Table 12. Experimental cross-sections have been used for these calculations. For deuterium and tritium targets forward direction (0° –lab) and for other targets 4π yields are given. In producing neutrons for medical and biological applications it is not only the flux that counts but the mean energy $\bar{E}_n$ of the neutrons also plays a very important role. $\bar{E}_n$ depends upon the target being used for neutron production as well as on the incident energy. Full consideration has to be given to it when fixing the maximum energy of a cyclotron if this is to be used for biomedical research work.

For neutron therapy the minimum accepted $\bar{E}_n$ is about 6–7 MeV, with a dose rate of at least 10–15 rad/min at a distance of about 100 cm from the target. Higher figures would be an advantage. The smallest machine fails to meet any one of these conditions. A usable neutron beam for therapy may be achieved from a 12 MeV compact cyclotron. Our calculations show that with this energy of deuterons, if a pure deuterium target could be realised, the resulting neutron beam should have an average energy of slightly over 8 MeV, and a dose of 40 rad/min at 100 cm from the target, for a beam current of 100μA.

Table 6. (p, 2n)

Maximum energy		16 MeV			24 MeV			32 MeV	
Z of the elements	20–40	41–60	61–83	20–40	41–60	61–83	20–40	41–60	61–83
Isotopic yield mCi/μA	22·8	76·5	122	338	616	405	611	983	542
Neutron yield n/s/μA	$1{\cdot}7 \times 10^9$	$5{\cdot}6 \times 10^9$	$9{\cdot}0 \times 10^9$	$2{\cdot}5 \times 10^{10}$	$4{\cdot}6 \times 10^{10}$	$3{\cdot}0 \times 10^{10}$	$4{\cdot}5 \times 10^{10}$	$7{\cdot}2 \times 10^{10}$	$4{\cdot}0 \times 10^{10}$
Detection sensitivity in oxygen matrix d.p.s./p.p.m./μA	$6{\cdot}0 \times 10^2$	$1{\cdot}6 \times 10^3$	$2{\cdot}4 \times 10^3$	$9{\cdot}2 \times 10^3$	$1{\cdot}4 \times 10^4$	$8{\cdot}0 \times 10^3$	$1{\cdot}7 \times 10^4$	$2{\cdot}2 \times 10^4$	$1{\cdot}0 \times 10^4$

Table 7. (α, 2n)

Maximum energy		24 MeV			32 MeV	
Z of the elements	20–40	41–60	61–83	20–40	41–60	61–83
Isotopic yield mCi/μA	5·6	2·9	2·1	33·1	16·3	18·2
Neutron yield n/s/μA	$4{\cdot}2 \times 10^8$	$2{\cdot}1 \times 10^8$	$1{\cdot}6 \times 10^8$	$2{\cdot}4 \times 10^9$	$1{\cdot}2 \times 10^9$	$1{\cdot}3 \times 10^9$
Detection sensitivity in oxygen matrix d.p.s./p.p.m./μA	$1{\cdot}4 \times 10^2$	$1{\cdot}1 \times 10^2$	$3{\cdot}5 \times 10^1$	$8{\cdot}4 \times 10^2$	$6{\cdot}5 \times 10^2$	$3{\cdot}6 \times 10^2$

Table 9. (p, 3n)

Maximum energy	24 MeV			32 MeV		
Z of the elements	20–40	41–60	61–83	20–40	41–60	61–83
Isotopic yield mCi/μA	0·2	5·5	69	70·4	363	547
Neutron yield n/s/μA	$2{\cdot}6 \times 10^7$	$6{\cdot}1 \times 10^8$	$7{\cdot}7 \times 10^9$	$7{\cdot}8 \times 10^9$	$4{\cdot}0 \times 10^{10}$	$6{\cdot}1 \times 10^{10}$
Detection sensitivity in oxygen matrix d.p.s./p.p.m./μA	6·4	$1{\cdot}2 \times 10^2$	$1{\cdot}4 \times 10^3$	$1{\cdot}9 \times 10^3$	$8{\cdot}2 \times 10^3$	$1{\cdot}7 \times 10^3$

Table 10. (α, 3n)

Maximum energy	32 MeV		
Z of the elements	20–40	41–60	61–83
Isotopic yield mCi/μA	0·7	0·4	1·2
Neutron yield n/s/μA	$7{\cdot}9 \times 10^7$	$4{\cdot}6 \times 10^7$	$1{\cdot}3 \times 10^8$
Detection sensitivity in oxygen matrix d.p.s./p.p.m./μA	9·8	$8{\cdot}4 \times 10^1$	$2{\cdot}0 \times 10^1$

Table 11. ISOTOPE PRODUCTION mCi/μA

Maximum energy					
d		8 MeV	12 MeV	16 MeV	20 MeV
α		16 MeV	24 MeV	32 MeV	40 MeV
^{3}He		21 MeV	30 MeV		
Reaction	*Isotope*				
^{11}B (d, 2n)	^{11}C	1	6	16	23
^{12}C (d, n)	^{13}N	60	100	137	171
^{16}O (^{3}He, p)	^{18}F	23	27	–	–
^{60}Ni (α, 2n) (80% enriched)	^{62}Zn	0	1·0	7·3	14·9
^{70}Ge (α, n) (80% enriched)	^{73}Se	2·7	16·7	21·7	22·0

Table 12. NEUTRON PRODUCTION n/s/μA

Maximum energy	d	8 MeV	12 MeV	16 MeV	20 MeV
	α	16 MeV	24 MeV	32 MeV	40 MeV
	^{3}He	21 MeV	30 MeV		
Reaction					
D (d, n)^{3}He (0° Lab.)		$6{\cdot}5 \times 10^9$	$2{\cdot}3 \times 10^{10}$	$5{\cdot}2 \times 10^{10}$	
T (d, n)^{4}He (0° Lab.)		5×10^9	2×10^{10}	$5{\cdot}2 \times 10^{10}$	
^{9}Be (d, n)^{10}B		$1{\cdot}2 \times 10^{10}$	$2{\cdot}5 \times 10^{10}$	4×10^{10}	7×10^{10}
^{9}Be (α, n)^{12}C		1×10^9	$2{\cdot}5 \times 10^9$	3×10^9	5×10^9
^{12}C (d, n_o)^{13}N		$1{\cdot}6 \times 10^9$	$3{\cdot}3 \times 10^9$	$5{\cdot}1 \times 10^9$	7×10^9

2. BEAM INTENSITY

The yields of isotopes and neutrons would go up with increasing beam intensity, but the maximum intensity that can be used is strictly limited by power dissipation in the target. Experience at Hammersmith Hospital shows that for most external bombardments the beam intensity has to be limited to ~50 μA though a few targets (metallic foils etc.) would stand up to 100 μA of spread-beam.

In some special cases it may be possible to use still higher intensities available in the internal cyclotron beam. These irradiations require special target construction to stand high-power density. In practice one seldom goes beyond ~300 μA for bombardment with an internal beam.

In radiobiology and nuclear physics the requirements are sometimes at the other extreme, and only nA of beam intensity are required. It is the authors' opinion that a compact cyclotron should be able to provide an internal beam of a few hundred μA and an external beam from a few nA to about 100 μA. As can be seen from the tables, sufficient yields can be obtained at these intensities. Much higher intensities may not be of great use in view of our present knowledge of target technology.

3. BEAM QUALITY AND ENERGY RESOLUTION

In the case of isotope and neutron production and of activation analysis the beam quality is important only for maintaining small beam size through the beam transport system and accurate determination of beam size at the target. Energy resolution is more or less unimportant in these fields. However, radiation biology does require good energy resolution to be able to obtain a well-defined Bragg Peak. But still the demands are not so high as in the case of injection into Tandems or in low-energy nuclear physics. The quoted energy resolution of ~0·2% and a beam quality of ~20 mm mrad by various manufacturers seem quite adequate for all these applications. Naturally, for high resolution nuclear spectroscopy one would have to use a beam analysing magnet in the external beam.

4. ENERGY AND PARTICLE VARIABILITY

For production of isotopes and neutrons and in activation analysis it is not absolutely essential to vary the machine energy although it can offer advantages. Maximum energy is generally used to obtain a maximum yield. However, in some cases it may be necessary to reduce the incident energy to suppress unwanted activities being produced simultaneously by competing reactions. Degradations of energy can be carried out by using absorber foils, as good energy resolution is not required, although beam current would then probably be limited by heating of the absorber foils rather than by target heating. In radiobiology, however, and more so in low-energy nuclear physics it would be of great advantage to have a beam of variable energy.

Most compact cyclotrons can accelerate p, d, ^3He and ^4He and as far as isotope and neutron production and activation analysis are concerned they are quiet adequate. However, accelerated beams of heavier particles would be of great use in radiation biology and nuclear physics.

CONCLUSION

We think it would be very advisable if the designers and manufacturers of compact cyclotrons concentrated on one standard size which should be the best compromise keeping in mind the potential applications of the machine and its cost. Our calculations may serve as a useful guide for reaching such an optimum. This cyclotron should be flexible enough to be offered in the following two versions.

(1) Fixed energy with no provision for accelerating elements heavier than ^4He. It should be relatively cheap and reliable in operation. Such a machine would attract attention from most hospitals and medical institutions which do more routine work and are not research orientated.

(2) A sophisticated version with variable energy and external ion source for heavier elements and polarised particles. This sort of cyclotron would naturally be more expensive and would be mainly attractive to research orientated biomedical and nuclear institutions.

This sort of rational designing, we think, would cut down manufacturers costs and would offer the best for their money to customers.

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DISCUSSION

Speaker addressed: M. A. Chaudhri (M.R.C., Hammersmith Hospital)

Comment by A. Van Kranenburg (N. V. Philips): The difference between a fixed energy compact machine and a variable energy compact cyclotron is rather a matter of soft-ware, than a matter of hardware. Therefore one should be careful in doing away with a variable energy machine for cost reasons, for the difference in cost is not large.

Question by K. V. Ettinger (U. of Birmingham): Have you considered how the cost of peripherals, e.g. beam transport devices and target handling equipment influences the cost of the machine installation?
Answer: The cost of the peripherals is almost independent of the machine size and has therefore been ignored in the comparison.

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