CYCLOTRON DESIGN STUDIES FOR A MEDICAL ION ACCELERATOR

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Abstract

A two year design study has been completed for medical ion accelerators with beams of sufficient range and intensity for therapy. The particles of main interest were ions between carbon and neon, but the generation of proton and neutron beams was studied also. Cyclotrons appear to be good injectors for a heavy ion medical synchrotron, particularly if neutron and/or isotope production is desired as well. They also offer a competitive solution for proton beams of 250 MeV. A superconducting cyclotron design for 380 MeV/u carbon was worked out, but a synchrotron for heavy ion beams of 400-600 MeV/u and 5 × 10^9 particles/sec was found to be more economical and flexible.

Introduction

This paper briefly summarizes the cyclotron portions and also the major conclusions of a 2 year medical ion accelerator design study at Lawrence Berkeley Laboratory. This study, carried out by a group led by one of the present authors, included work on a number of accelerator, beam delivery and medical topics, and is summarized in a Final Report[1], which provides much more information than can be presented here. A short summary was also given in Ref. 2. The goal of the study was to provide preliminary design of accelerator and beam delivery systems which would meet the medical requirements for ion beam therapy, radiography and perhaps also isotope production. Concerning the choice of ions, the greatest emphasis was given to heavy ions between carbon and neon, because of their unique combination of biological and physical advantages. The other particles considered were protons and neutrons. Emphasis was placed on using proven technology, which would guarantee highly reliable accelerator performance in a hospital environment.

Medical Requirements

The relation of range vs. energy for ions of interest is given in Fig. 1. For effective therapy in the human body, the range in tissue should be about 30 cm. This determines the beam energies needed, which are shown in Table 1. The required beam intensities, also in Table 1, are obtained from the desired dose rate: 600 rad-liter/min in a 1000 cm^3 volume of shallow depth (2 cm), allowing for losses due to beam transport and field shaping. The requirements on emittance and energy spread are met by typical present accelerator beams. A macroscopic duty factor of at least 25% is desireable for beam scanning and monitoring systems.

Cyclotron Injectors

This study concluded that the preferred system for producing beams of carbon and neon consists of a cyclotron or linear accelerator injecting a synchrotron. Either injector will supply adequate beam intensity, but a cyclotron could also produce isotopes and neutrons with its light ion beams. Cyclotron injectors are described here.

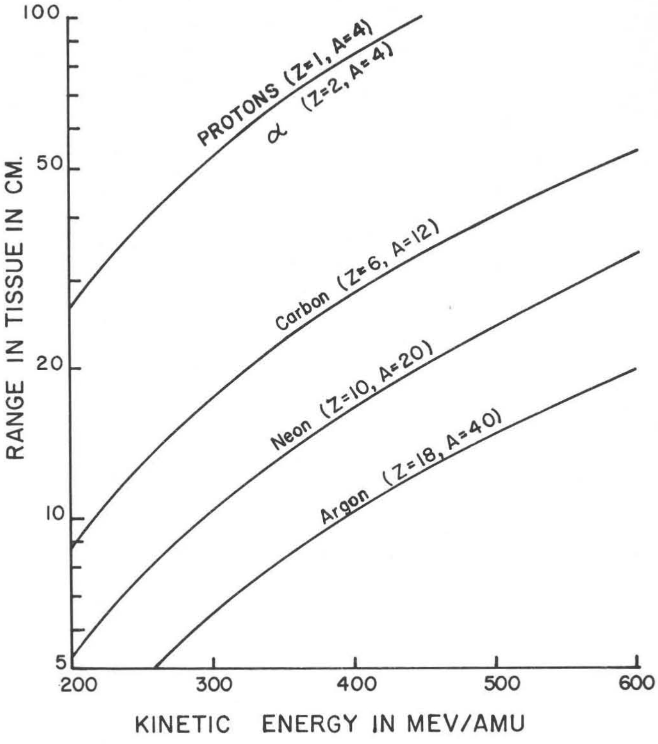

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Fig. 1. Range in tissue for ions of interest as a function of their kinetic energy.

Table 1. Beam specifications for accelerators.

Particle	Extracted Flux(s^{-1})	T_{max} (MeV/u)
p	8 × 10^{10}	200 to 250
α	2 × 10^{10}	200 to 250
C	4 × 10^9	380 to 430
Ne	2 × 10^9	525 to 575

The first component which determines the beam intensity of a cyclotron is the ion source. The ion source assumed here is the PIG source used in most heavy ion cyclotrons and linacs. The beam intensities available of the various charge states of carbon and neon beams are shown in Table 2. The total output is assumed to be 10 emA. If charge state 1 is required, all the current is assumed to be in that charge state. If a charge state of 2 or more is required, the charge state distribution of Bennett[3,4] is assumed.

Table 2. Ion source output, emA, dc.

	Charge State				
	1^+	2^+	3^+	4^+	5^+
Carbon (CO)	10	2.3	.8	.1	.001
Neon	10	4.3	3.6	.8	.2

The main accelerator should be injected with fully stripped ions to minimize its size and cost. The injector energy must then be sufficient to fully strip a good fraction of its external beam in a stripping foil. Data on equilibrium charge state distribution after a stripping foil, vs. energy was obtained from Ref. 5 for carbon

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and from recent measurements by Alonso at LBL[6] for neon.

The current of fully stripped ions after the stripping foil can be calculated from the ion source output, the transmission factors from the source through the external stripping foil, and space charge limitations during acceleration. For the transmission factors we assume .33 from dc source to accelerated beam in the center region for an external ion source with bunching, and .125 for an internal source. We assume .5 for transmission through the acceleration region and .5 for extraction. The transmission through the stripping foil is given by the accelerated charge state, the cyclotron K and Ref. 5,6. The space charge limit was obtained by taking half the theoretical limit of Blosser and Gordon,[7] letting the full dee aperture = .02 m, magnetic field = 1.5 T, ν_z = .1, phase width = .75 radians, and voltage gain/turn = 250 kV. The resulting currents of fully stripped ions vs. cyclotron K are shown in Fig. 2 for carbon and Fig. 3 for neon. The currents are lower than in Ref. 1 because here lower transmission factors are used and the space charge limit is added. The injected currents required by the synchrotron to satisfy Table 1 are also shown. Another factor which comes into play in the selection of a cyclotron K and charge state is the RF frequency range of the synchrotron. This range should be kept below 10 to 1, requiring a large K and Q (K > 40 for C^{3+} and K > 70 for Ne^{4+}).

Conceptual designs and preliminary cost estimates were worked out for 10 cyclotron injectors with variations of design and performance. They are shown in Table 3. The base cost does not include design, control room, computer control or contingency. The table indicates that injectors with $\bar{B}$ of 1.5 T and 2.0 T have about the same cost, and that a split pole design costs 40% more than a single pole design. Also the cost increases slowly with K for these small cyclotrons, and only a modest additional cost is required to add protons through α-particles to the heavy ion capability. Design 8 is a purchased, commercial machine, modified for use as an injector.

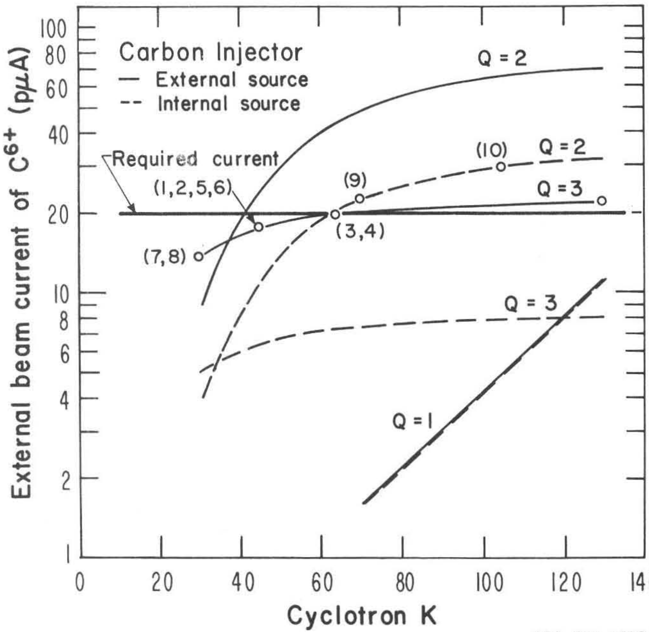

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Fig. 2. Currents of C^{6+} available from an injector cyclotron after stripping vs. cyclotron K value. Q is the charge state during acceleration. Numbers in parentheses are design cases studied.

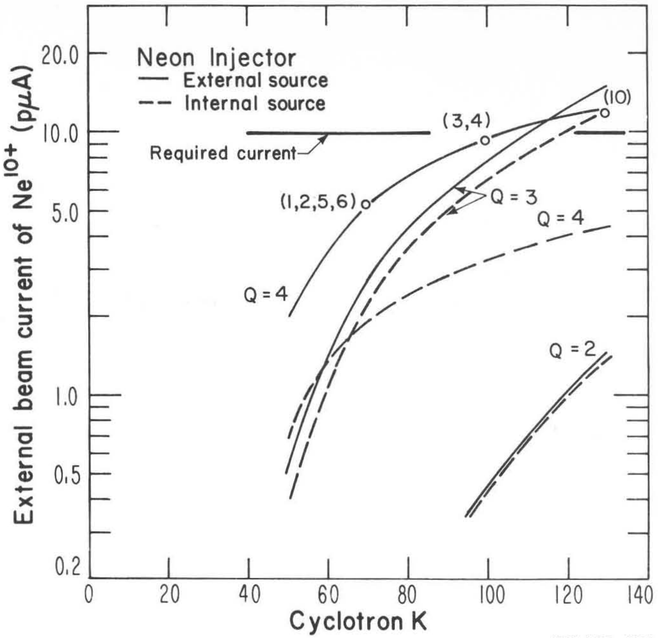

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Fig. 3. Currents of Ne^{10+} available from an injector cyclotron after stripping vs. cyclotron K value, plotted as in Fig. 2.

Table 3. Summary of cyclotron injectors.

Design #	1	2	3	4	5	6	7	8	9	10
K	70	70	100	100	70	70	30	30	70	130
$\bar{B}$ (T)	2.0	1.5	2.0	1.5	1.5	.9	1.5	1.9	1.5	1.5
Source	ext	ext	ext	ext	ext	ext	ext	ext	int	int
Particles	C→Ne	C→Ne	C→Ne	C→Ne	p→α C→Ne	C→Ne	p→α C	p→α C	p→α C	p→α C→Ne
Comments						split-pole		purch.		neutron beams
Base Cost (1977 M$)	2.11	2.14	2.26	2.31	2.42	3.04	2.02	1.93	2.14	2.80

The largest of the group, design 10, is shown in Fig. 4 to illustrate the design philosophy used for most of the cases. Two dees in valleys are used with 4 sectors. $\bar{B}$ = 1.5T. Trim and harmonic coils are included. 2 RF frequencies and harmonics 3,4,5 make possible the acceleration 2.9 MeV/u C^{2+} and Ne^{3+}, 65 MeV d for neutron production, and p, d, ^{3}He and α-particles for isotope production.

Cyclotrons as Main Accelerators

The choices for a main accelerator to produce 400 MeV/u carbon or 550 MeV/u neon include synchrotrons, cyclotrons and linear accelerators. The linac was rejected on an economic basis. The synchrotron will produce adequate intensity and fast energy changes which are useful in depth scanning, but is a complex accelerator and occupies a large area (24 m diameter for the carbon case).

A cyclotron for carbon would have a very large K value of over 2000 using C^{5+}. The largest existing cyclotrons have K ≃ 600 (SIN, TRIUMF) and the largest machine being designed has K = 800 (M.S.U., superconducting). Previous studies show[8] that a superconducting design is much cheaper in these large sizes. A conceptual design was worked out for a superconducting FM-Cyclotron for 380 MeV/u C^{5+}, which also produces 100 MeV/u deuterons for neutron production. The FM mode would be used for C^{5+} and enough sector focusing would be provided to use the CW mode for deuterons at low magnet excitation. The C^{5+} would

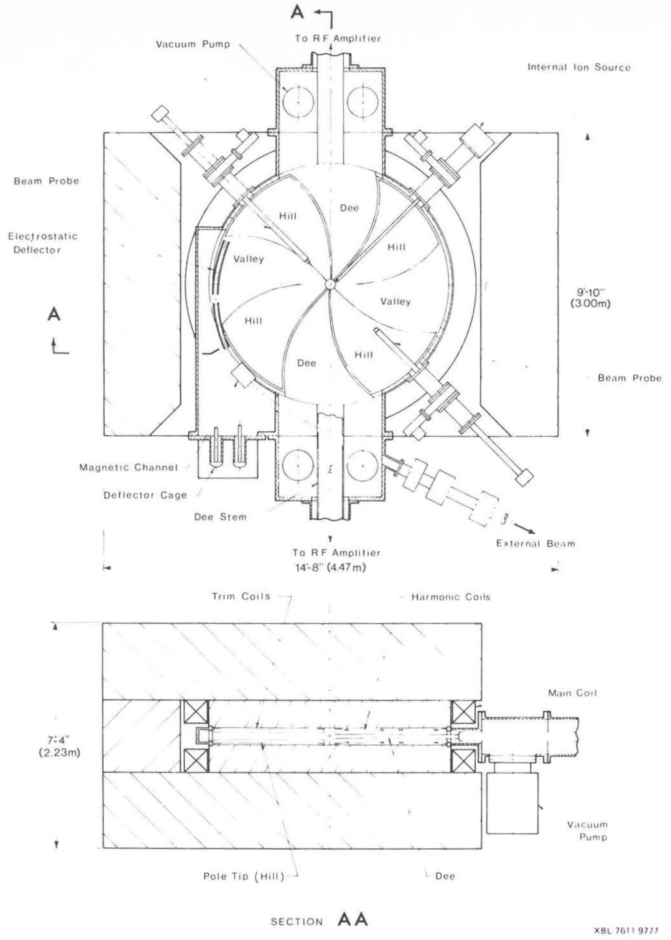

Fig. 4. Injector cyclotron for ions up to neon, with K=130. It can also generate neutrons and produce isotopes.

provide sufficient beam intensity and be stripped to C^{6+} for 100% extraction of good quality beam. A layout of this design is shown in Fig. 5. The cost is shown in Fig. 6. A CW superconducting cyclotron is also a possibility for C^{5+}, and would have a similar cost to the FM design above.

Another conceptual design was done for a fixed energy 250 MeV isochronous proton cyclotron with normal conducting coil. It uses a 2 T field and 2 dees in valley similar to a previous design[9] for 150 MeV p. Its cost is also shown on Fig. 6.

The base cost vs. K for all main stage cyclotrons and synchrotrons studied is shown in Fig. 6. The cost includes injector, control room, computer control and installation, but not design, building, shielding or contingency. The curve for "Superconducting Cyclotrons" has been adjusted downward slightly from the Ref. 1 position to pass through the corrected C^{5+} point. The synchrotron is the best candidate for carbon and neon beams because of its cost advantage and its energy variability. For protons the cyclotron is cheaper but the synchrotron has the advantage of variable energy. The base cost of a whole facility of accelerator, beam delivery, and 4 treatment rooms is expected to be 13-15 M$('77). A layout of a possible facility is shown in Fig. 7.

Acknowledgements

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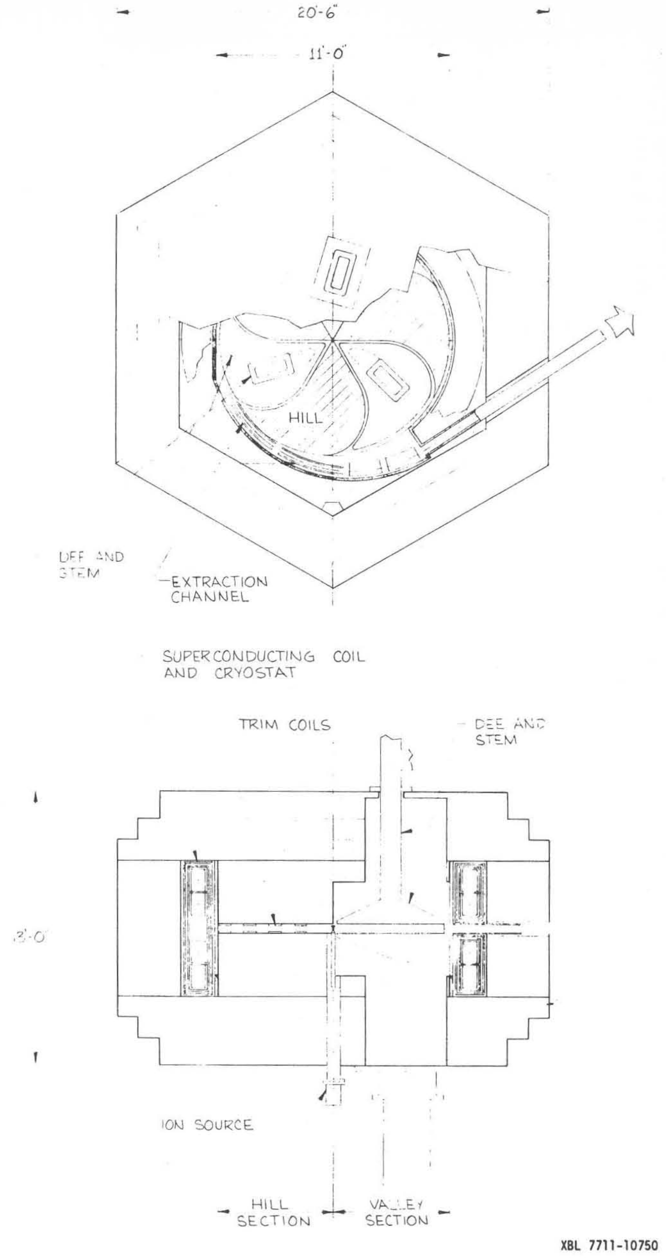

Fig. 5. Superconducting FM Cyclotron for 380 MeV/u C^{5+} ions.

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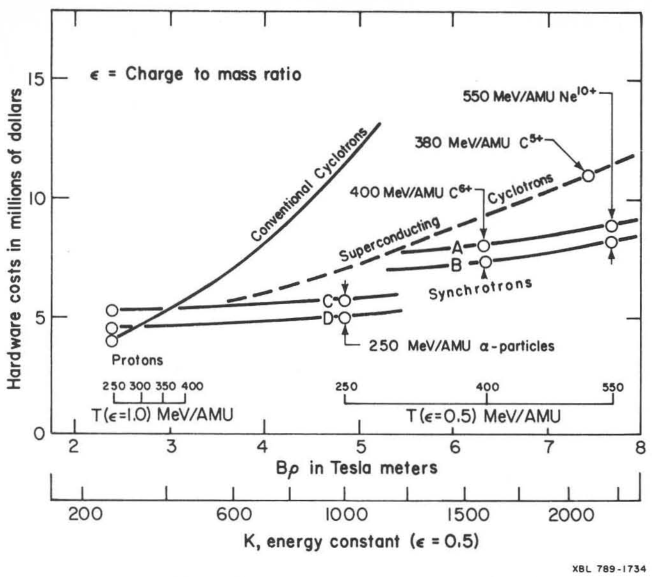

Fig. 6. Cost and performance summary of circular accelerators. Cost is base cost (excluding design) in FY '77 $. The synchrotrons A, B, C, D have different injectors: A-heavy ion injector with neutron and isotope production; B-heavy ion injector with isotope production; C-p,α injector with isotope production; D-p,α injector only.

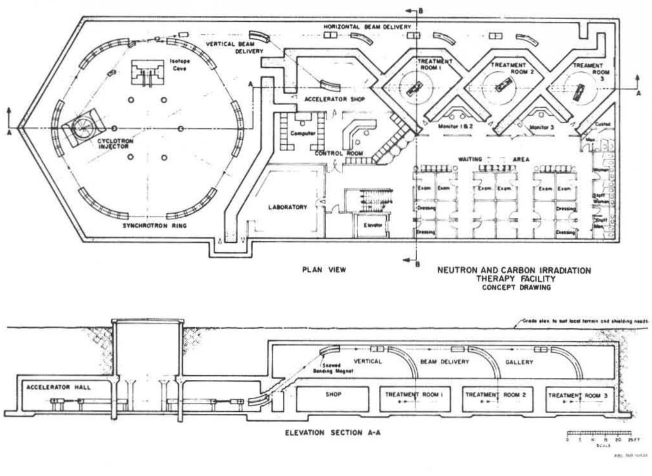

Fig. 7. Conceptual facility layout showing a cyclotron injecting a synchrotron. Horizontal and vertical beams are available in 3 treatment rooms.

** DISCUSSION **

J. BLASER: Did you study beam lines, including beam rotation around the patient? What would be the cost, and would one consider superconducting beam optics?

D. CLARK: The medical people agree that if one has one vertical beam and one horizontal beam, then the ability to rotate the patient on a table would give enough flexibility. An isocentric gantry was considered, but it is more expensive. In considering these cases we assumed room temperature beam transport and scanning magnets because of their proven reliability, but superconducting magnets may offer some space and cost savings for a gantry system and should be reconsidered in the future.

K. ERDMAN: Have the people in California decided which are the best heavy ions to use for medical therapy?

D. CLARK: The best heavy ions are still believed to be between carbon and neon, and research is continuing on this point to narrow the range further. For argon, fragmentation broadens the Bragg peak, making it less desirable, except for surface irradiation.

H. BLOSSER: What are the factors that lead you to conclude that an external source would give higher current in your injector cyclotron? Is there experimental data?

D. CLARK: The principal factor in the superiority of the external source is the ability to bunch the beam, while the internal source only chops the beam as it leaves the source. There is not experimental data at these high currents—we have extrapolated.

R. KOUZES: If the evidence shows that carbon is the heaviest useful particle for therapy, would the superconducting cyclotron be the machine of choice?

D. CLARK: No, the study shows that the cyclotron-plus-synchrotron combination is still most cost effective for ions heavier than protons.

G. GORDON: What factors were evaluated in arriving at cost comparisons between superconducting cyclotrons and conventional ones?

D. CLARK: The factors considered were the costs of fabricating the individual components in each cyclotron and the cost of assembly and installation. Design costs were not included, nor were costs for shielding or beam transport. Most components of superconducting cyclotrons are similar to those in normal cyclotrons, except for the superconducting coils.

M. CHAUDHRI: What sort of technical manpower would be required in a hospital to be able to make the full use of this sort of machine and provide all the service and back-up facilities?

D. CLARK: We would expect to have 8 people to operate and maintain a synchrotron facility for an 8 hour per day schedule. Their jobs include operating, electrical and mechanical maintenance, and computer maintenance and programming. For a 16 hour per day schedule we would need 12 people. These people should be trained during the final construction period. This level of technical support assumes a strong emphasis on reliability in the design and construction phases, using techniques such as modular design, adequate spare parts, and self-diagnosis by the computer system.

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