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A HEAVY ION FACILITY FOR RADIATION THERAPY

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Summary

The accelerator requirements of particle radiation therapy are reviewed and a preliminary design of a heavy ion synchrotron for hospital installation is presented. Beam delivery systems and multi-treatment room arrangements are outlined.

Introduction

A broad future application of particle beams in radiation therapy demands hospital-based accelerators designed for cost-effectiveness, high reliability and modest operations and maintenance crews. We discuss here machines capable of deliverying therapeutic ion beams, protons to neon, emphasizing carbon for purposes of detailed illustration and including the capability of producing neutron beams.

Beam Specifications

Particle species, energy and beam intensity determine the design of the optimal accelerator type. The energy is determined by the required range, the atomic number Z and the mass number A of the beam (Figure 1). Typical ranges for therapy fall between 25 and 32 cm. Radiography requires slightly higher energies than therapy or must be performed with lighter ions.

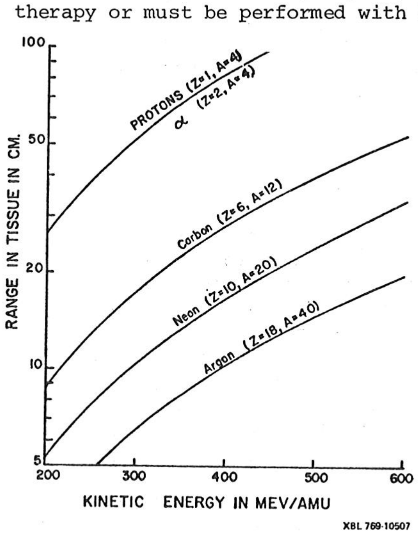


Figure 1: Range in tissue vs. energy

Design beam intensities are derived from the required dose rates and treatment volumes. An ideal goal is 200 rad/min in a volume 30 cm x 30 cm cross section and 15 cm depth. Approximate corresponding beam intensities are:

PARTICLE	FLUX (s^{-1})
p	$2.5 \cdot 10^{10}$
α	$6.25 \cdot 10^{9}$
C	$1.0 \cdot 10^{9}$
Na	$5.0 \cdot 10^{8}$

*This work was done with the support of the National Cancer Institute of the Department of Health, Education, and Welfare.

Advanced beam delivery system (e.g. 3-dimensional scanning[1]) require in addition a macroscopic machine duty cycle of about 50%.

It would be a valuable asset of a large therapy facility if it included the capability to produce radioisotopes for nuclear medicine and possibly neutron beams for therapy. Radioisotope production can be accomplished with proton or deuteron beams below 30 MeV while neutron production demand energies between 30 and 100 MeV and beam currents between 10 and 100 μA.

Choice of Accelerator Type

The following table summarizes possible accelerator options capable of delivery therapeutic heavy ion beams:

ACCELERATOR	BEAMS			RELATIVE COST	COMMENTS
	HI	n	isotopes		
Linac	X	X	X	high	
Cyclotron Conventional	X	X	X	high	
Superconducting isochronous cycl.	X	X	X	high(?)	substantial R&D
Superconducting FM-cyclotron	X	X	X	moderate	modest R&D
Synch + VdG	X			low	HI limited to α
Synch + linac	X			low	
Synch + cyclotron	X	X	X	low	

An additional survey of estimated hardware costs and capabilities of circular accelerators is contained in Figure 2.

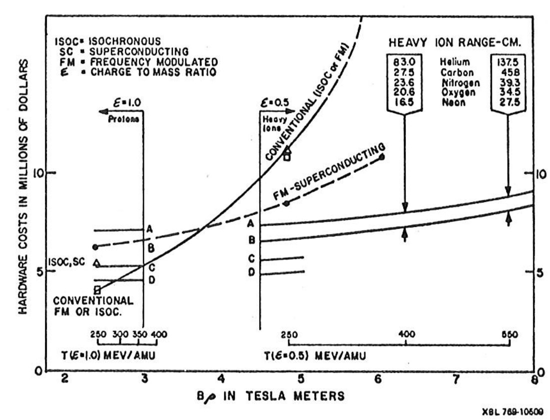


Figure 2: Cost of circular accelerators (incl. injectors)
A. Synchrotrons with neutron and isotope production
B. Synchrotrons with isotope production
C,D Synchrotrons for α particles only, with and without isotope production.

We studied in detail a sector focused, superconducting FM-cyclotron with an internal ion source. Up to approximately 100 MeV/amu an isochronous field would be maintained allowing the production of intense deuteron beams for neutron therapy. At a field level <B> $\sim$ 4.8T C^{+5} beams are accelerated to $\sim$400 MeV/amu. An extraction scheme, based on stripping the beam into C^{+6} and the use of a magnetic channel, was shown to be essentially 100% effective and to conserve good beam quality. We slightly favor synchrotons in the proposed application for their lower cost and, most important possibly, greater flexibility in terms of available beams and beam energies.

Synchrotron Design and Optimization

A cost-optimized design of a synchrotron providing beams from protons to neon at the initially specified intensities is attempted. Maximum design energy is 415 MeV/amu ($B\rho$ = 6.5 Tm for $^e/_m$ = 0.5, range in tissue $\sim$28 cm for carbon). Modest changes in peak energy will not alter the basic design and corresponding incremental costs are indicated in Fig. 2. For simplicity and reliability mechanical activators, plunging magnets and MG-sets will be absent. The use of cannea magnets is planned.

Injectors

The specifications for an injector are based on a PIG ion source.

The injection energy should be high enough to yield a sufficent beam of fully stripped ions and keep the synchrotron RF-frequency swing modest ($\sim$10:1). Table 1 illustrates the dependence of available C^{+6} current on energy for different accelerated charge states based on typical ion source performance.

Injection Energy (MeV) & $\downarrow$RF-swing	Carbon Charge State Accelerated in Injector $\rightarrow$ +2	+3	+4
1 (15.6:1)	6.5 (52)	1.5 (12)	0.14 (1.13)
2 (11.1:1)	23 (187)	5.4 (43)	1.0 (8.1)
3 (9.0:1)	30 (239)	8.3 (67)	0.8 (6.3)

Table 1: C^{+6} current vs. injection energy and charge state used in injector.

The currents are given in pμA. Values in parentheses apply for a linac or external source cyclotron, the others to an internal source cyclotron. Currents of 30 pμA result in efficient synchrotron designs operating not to far from a space charge limited condition. In terms of overall economics an internal source cyclotron accelerating C^{+2} (or Ne^{+3}) or a linac accelerating C^{+3} to energies between 2 and 3 MeV are the preferred solutions.

Table 2

Typical Beams from Injector Cyclotron

Ion	h = Harmonic	E (MeV/amu)	f_{RF} (MHz)	$\sin\left(\frac{h\theta_D}{2}\right)$
D^+, H_2^+, α	3	32.5	33.2	0.92
D^+, H_2^+, α	4	17.9	33.2	1.0
D^+, H_2^+, α	5	11.3	33.2	0.92
$^{12}C^{+2}$	3	2.9	10.0	0.92
$^{20}Ne^{+3}$	3	2.9	10.0	0.92

Table 2 lists beams available from a K = 130 isochronous cyclotron with an RF-system with 2 fixed frequencies (4 dee's, θ_D=45°). Voltage drop accelerators ($\sim$3 MV) seem tp be inadequate for HI operation.

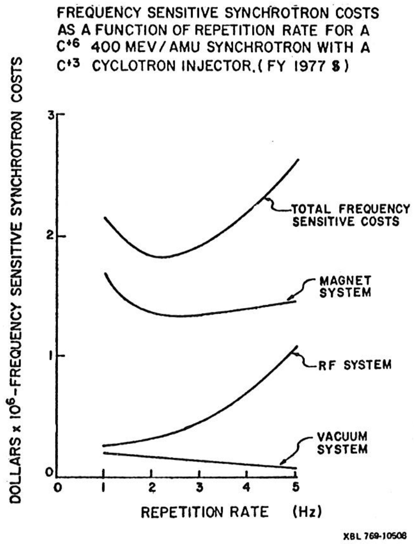


Figure 3: Frequency dependent synchrotron costs.

Synchrotron Repetition Rate

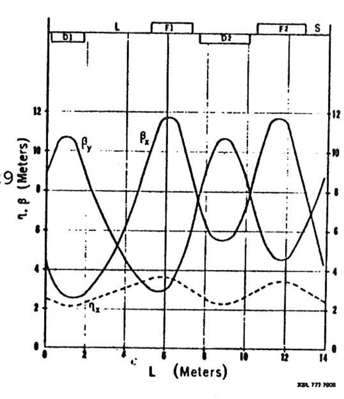
Obviously a trade-off between magnet aperture and repetition rate is involved in designing a synchrotron for a given average beam intensity. Aperture is determined by space charge for the lighter ions, by injector brightness for the heavier ones. Assuming expected values for β-functions and stacking efficiencies values of f_{rep} were optimized with respect to magnet, magnet power supply and RF-system costs. Optimum values differ for different injector types but all fall in the range from $\sim$1 Hz to 3 Hz, with 2 Hz being specified for the present design (Fig. 3).

Synchrotron Lattice

The main goals in designing possible lattice configurations were: to utilize the magnet aperture efficiently by minimizing β-functions, to facilitate magnet design, construction and alignment by keeping tunes faily low and to obtain a transition energy above the design peak energy. The lowest periodicity meeting these requirements is six. Six periods, each containing a long and short straight section, provide suitable positions for injection, extraction and correction elements as well as an accelerating cavity and diagnostic equipment. Both combined and separated function lattices with the desired properties have been designed. The combined function lattice, similar to the ANL PSB design[2], has the advantage of fewer elements and independent parameters and is preferred for this application.

Table 3 and Figure 4

Beam Rigidity	6.5 Tm
Number of Periods	6
Guide Field	0.8 T
Sequence	DOFDFO'
Mean Radius	13.22 m
ν_x, ν_y	2.31, 2.29
γ_{tr}	2.14
Aperture	10cmx4cm
Field Index	$\pm$13.1
$\hat{\beta}_x$	11.7 m
$\hat{\beta}_y$	10.8 m



Injection and Acceleration

30 pμA of C^{+6} ions are expected from the injector cyclotron. About 25 turns must be injected requiring a full radial aperture of 10 cm.

Injection uses an electrostatic septum located in one of the long straight sections. The closed orbit is controlled by a pair of small kicker (peak field 20 mT). The beam is captured and bunched adiabatically in 150 μs with $\dot{B}=0$ and then accelerated for 125 ms. Maximum space charge induced ν-shift occurs after bunching and is estimated to be 0.04. The acceleration system employs a drift-tube type cavity located in a long straight section and operates at the first harmonic allowing the required frequency swing (0.31 to 2.9 MHz) to be obtained with available ferrites.

Extraction

Slow extraction is required to obtain a high duty factor. We plan to re-examine energy loss extraction schemes but at present choose resonant extraction at $\nu_x = 7/3$. Two pairs of quadrupoles control vertical and radial tune while the extraction non-linearity is provided by two sextupoles of opposite polarity located diametrically. For simplicity and reliability the septum is not plunged. While growth must be rapid enough to ensure low losses at the septum it should not be so strong as to increase the emittance of the extracted beam. This is achieved by locating the extraction septum immediately following the defocusing singlet and one extraction sextupole immediately upstream of the singlet.

Beam Delivery and Facility Layout

Number of treatment rooms

Any viable facility must be able to handle a certain patient load typically stated as the number of new patients per year. Treatments are fractionated, i.e. the total dose is delivered in a number of individual irradiations (fractions) over a period of a few weeks. Typical values are about 250 rad per fraction for a total dose of 6 to 8 krad. With the specified beam intensities a single fraction can be delivered in $\sim$1 min. With a set-up time of 15 min. for each treatment this will allow 30 treatments per 8 hour day or about 300 new patients per year and treatment room. Clearly an accelerator of the considered type can efficiently deliver beam to several treatment rooms. This will not only increase the possible patient load but may also allow longer set-up times and provide the capability to absorb short duration interruptions in machine operation. Fig. 5 shows a conceptual layout of a facility. Many other arrangements are obviously possible and total floor space requirements can be shrunk to $\sim$900 m^2 for a facility with only two treatment rooms located inside the synchrotron.

Beam Delivery Systems

Beam handling techniques are needed which allow the irradiation of large volumes to homogeneous, well defined dose levels. A novel approach involving 3-dimensional beam scanning[1] is being investigated by the authors. Furthermore variable directions of the incident beam are desirable with a fixed horizontal and a fixed vertical beam being minimum requirements. Complete flexibility is obtained with isocentric beam transport systems. Such systems can be built at a cost approximately 25% to 30% higher than a fixed horizontal and vertical beam. A system for 400 MeV/amu C ions, incorporating a scanning system and rotating through 360° occupies a cylindrical volume of about 15 m length and 5.6 m radius. The use of superconducting magnets has been explored in a system containing the required beam spreading devices (scanning or scattering) the gain in overall size is nominal compared to the added complexity of the cryogenic system.

Operational Aspects

Peak power demand for this facility is estimated to be about 2.7 MW (0.25 for injector, 1.85 synchrotron (peak), 0.6 for one isocentric delivery system). Average consumption is less of course and if the synchrotron and beam lines are powered only during treatments, average power for a 3-treatment room facility is well below 1 MW. A total operations and maintenance staff of at most 10 members is aimed at. A self-diagnosing computer control system is necessary to achieve this. This aspect is studied and experience from the SuperHILAC/Bevalac system indicates that this is a realistic goal for a medical accelerator in routine operation.

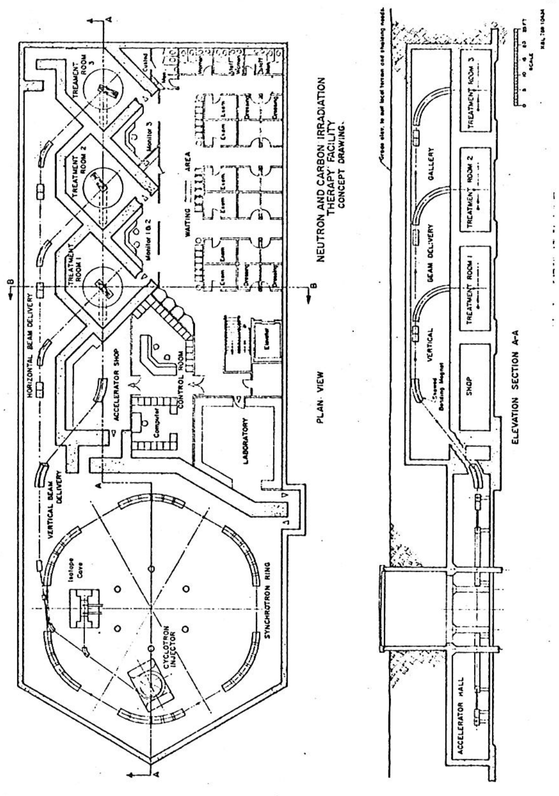


Figure 5: Conceptual Facility Layout

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1. Ch. Leemann et al., A 3-Dimensional Beam Scanning System for Radiation Therapy, this conference.

2. E.A. Crosbie, et al., The Design of the Zero Gradient Synchrotron Booster II-Lattice, IEEE, NS-22, No. 3, 1975, p. 1919-1921.