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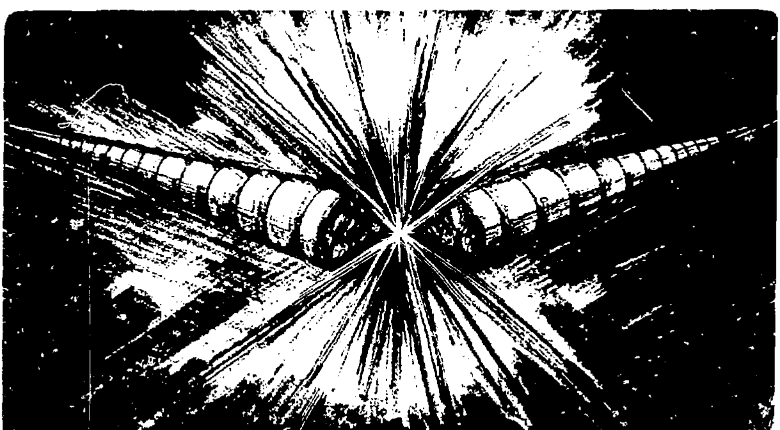

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Summary

This report describes the design of an advanced medical facility dedicated to charged particle radiotherapy and other biomedical applications of relativistic heavy ions. Project status is reviewed and some technical aspects discussed. Clinical standards of reliability are regarded as essential features of this facility. Particular emphasis is therefore placed on the control system and on the use of technology which will maximize operational efficiency. The accelerator will produce a variety of heavy ion beams from helium to argon with intensities sufficient to provide delivered dose rates of several hundred rad/minute over large, uniform fields. The technical components consist of a linac injector with multiple PIG ion sources, a synchrotron and a versatile beam delivery system. An overview is given of both design philosophy and selected accelerator subsystems. Finally, a plan of the facility is described

Introduction

The current heavy ion radiotherapy program at the Bevalac has been underway since 1975. Ions throughout the periodic table are accelerated to energies of approximately 1 GeV/nucleon. The availability of these unique beams has led to a broad range of research activities in the nuclear and biomedical sciences. The radiotherapy program is routinely scheduled 4 days per week during the hours 8 a.m. to 4 p.m. At all other times the machine is scheduled for nuclear physics. There is presently only one room for patient treatment, which, coupled with patient set-up time and the overall complexity of the facility, represents a basic limitation of present facilities.

While there is a continuous effort to improve the efficiency of the current program, there are certain limitations which must be recognized. First the Bevalac is a dual purpose facility with growing demands from the physics and nuclear science program as well as from the biomedical and radiotherapy program. Therefore, even with continuing improvements, little reduction in operational complexity is anticipated. Second, the Bevatron was designed over 30 years ago as a high energy physics proton accelerator. Operations, maintenance and especially today's electrical power costs present an increasing demand on available resources. It is very clear that a single purpose modern facility will be more efficient in meeting the increased demands of the heavy ion radiotherapy program. Such a facility could increase patient throughput from 10 to over 100 patients/day and could be sited at or near a major hospital complex.

In August 1981, a three year effort was initiated to design a new heavy ion radiotherapy facility.[1] Specific objectives of this program are:

1. to assess the requirements of all potential users.
2. to provide a fully optimized and detailed design of all components of the accelerator, beam delivery systems, treatment areas and conventional facilities.
3. to provide detailed construction costs and schedules and estimates of operating costs.

General Requirements

The requirements summarized in Table 1 are based on current LBL programs and studies[2] over the past ten years.

Table 1: Medical Accelerator Requirements

Particle Species:	^{4}He thru ^{40}Ar
Energy range:	70-800 MeV/amu
Intensity:	$\geq 3 \times 10^7$ Si ions/s on target
Field uniformity:	± 2% over 30 cm diam. field
Duty factor:	20 - 50%
Reliability:	> 95%
No. of beam rooms:	4 patient radiotherapy 1 patient radiography 3 other biomedical uses
Special beam orientations:	1 vertical down radiotherapy beam

As can be seen from the range energy curves in figure 1, a maximum energy of 800 MeV/amu is

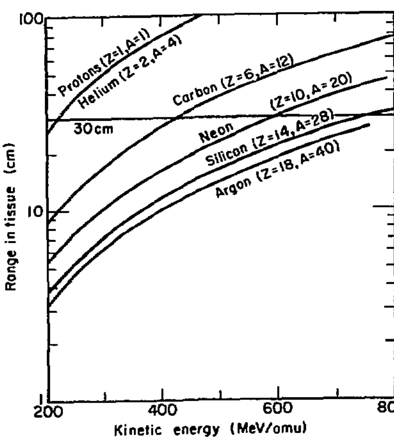

Figure 1: Range energy curves.

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sufficient for treatment sites which are 30 cm deep or greater for all ions up to argon. A minimum intensity for silicon of 3 x 10^7 ions/s will permit most treatments to be administered in 1-2 min.

Design Philosophy

The general goals that are of foremost importance in the design of a medical accelerator are the achievement of reliability, safety, and simplicity of operation. Accordingly we have chosen to follow the philosophy of using proven technology wherever it is possible.

A previous LBL study[2] made a detailed comparison of various types of accelerators and their relative cost versus energy. From this information and the requirements of the previous section, it has been determined that a strong focusing synchrotron will achieve these objectives most economically. An intensity schedule for such a machine is shown in Table 2.

Table 2: Intensity Schedule for Silicon Ions

	Intensity	Flux (Particles/s)
Instantaneous ion source output	2 mA	3.0 x 10^{15}
Instantaneous injector output	720 μA	3.2 x 10^{14}
Synchrotron output (4 Hz)	2.3 nA	1.0 x 10^9
On target (Passive beam delivery, 10% efficiency)	200 rad/min	1.0 x 10^8

Description of Selected Technical Components

Synchrotron Parameters

Synchrotron parameters are shown in Table 3. The circumference of 91.8 m is determined by the peak energy, the maximum magnetic field of the bending magnets and the lattice arrangement of the bending and focusing magnets. The lattice arrangement consists of 12 bending magnets and 18 quadrupole focusing magnets.

Table 3: Synchrotron Parameters

Peak energy	800 MeV/amu
Injection energy	8 MeV/amu
Circumference	91.8 m
Maximum Cycle rate	4 Hz
Tune	2.3
Momentum spread	±0.4%
Bend Magnets	
field	1.6 T
length	3.2 m
aperture	4 cm x 9 cm
power/magnet	46 kW
Quadrupole Magnets	
B'	6.94 T/m
length	0.4 m
aperture	10 cm diam.
power/magnet	4 kW

Injection System

The injection system parameters are shown in Table 4. While a radio frequency quadrupole (RFQ) has not been used in previous accelerators, a prototype model is under construction as part of the upgrade project for the Bevatron local injector[3]. On-line operation of this prototype will demonstrate the reliability of the RFQ and its suitability for the medical accelerator.

Table 4: Injection System

	Ion	Energy
Ion Source (50 kV)	Si^{4+}	7.1 keV/amu
RFQ (2.5 m)	Si^{4+}	230 keV/amu
Alvarez I (8 m)	Si^{4+}	1750 keV/amu
Stripper	Si^{10+}	1750 keV/amu
Alvarez II (10 m)	Si^{10+}	8000 keV/amu
Stripper	Si^{14+}	8000 keV/amu

o All linacs operate at 200 MHz with low duty factor
o Single-turn injection into synchrotron

Controls

The control system for the Medical accelerator is one of the most important elements. A summary of the control system requirements and the design philosophy is indicated in Table 5. In general, the input/output data, monitoring, control and operator displays will be handled by a large number of microcomputers such as the Intel iAPX 286. This is similar to the system now in use for one of the injectors at the SuperHILAC. Automation, and other high-level control functions will be provided by a powerful minicomputer such as the VAX 11/780. This is similar to the system that has been developed for the PEP (positron-electron project) storage ring at the Stanford Linear Accelerator Center (SLAC). We are drawing heavily on our experience in developing the above systems with modifications and improvements to match the specific needs of the medical accelerator.

Table 5: Control System

Requirements:

1. Provide safe and reliable operation of accelerator.
2. Monitor or control about 3000 signals.
3. Provide fast response (4 Hz max repetition rate).

Design Philosophies:

1. Automated diagnostics and beam line tuning.
2. Modular design of hardware and software.
3. Cost-effective designs: buy whenever possible.
4. Flexibility to deal with changes.

Acceleration and Beam Extraction

The acceleration cycle is shown in figure 2 in terms of magnet current versus time for the typical (2Hz) and maximum (4Hz) repetition rates. Beam extraction occurs at the prescribed beam energy with a 60% duty cycle at the peak energy (2Hz) and corresponding higher duty cycles for lower energies.

A resonant extraction system will be utilized. A third integer resonance is excited by perturbing quadrupole and sextupole magnets. The perturbed beam in the outer part of the magnet aperture is then extracted via a .25 mm electrostatic septum followed by a 7.5 mm magnetic septum. The extraction efficiency is projected at 70% to 90% depending on the energy.

Beam Delivery System

The large uniform fields required at the treatment site can be achieved by the scattering foil - occluding ring system currently in use at the Bevatron and the 184" Cyclotron[4]. While this system accomplishes the desired goals, it is somewhat cumbersome and inefficient. Beam scanning systems offer certain advantages[2] over the above method, namely, cleaner beams, improved beam efficiency, rapid field-size changes, and the potential for 3-dimensional fielo scanning. Two fast pulsed magnets are being prepared for a 2-dimensional scanning system at the Bevatron during the coming year. This development will serve to optimize this technique for the new medical accelerator.

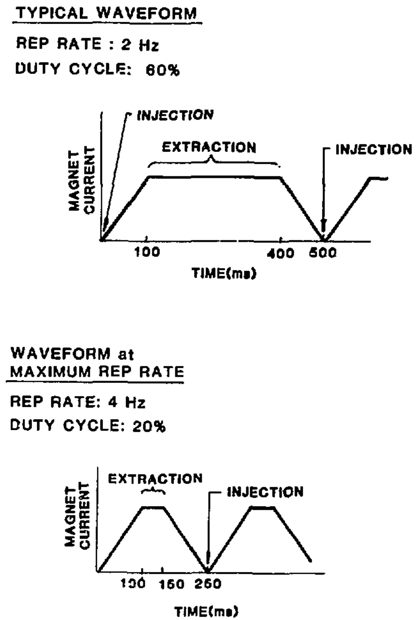

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Figure 2: Acceleration Cycle waveforms for typical (2 Hz) and maximum (4 Hz) repetition rate.

Facility Plan

Figure 3 shows a conceptual layout of the accelerator system and 8 heavy ion beam rooms. The empty room in the lower left corner represents the size of a typical treatment room for conventional photon radiotherapy. The heavy ion treatment room just above it could be equipped with both a vertical and a horizontal beam delivery system. The rooms which are arranged around the large open area at the bottom are for radiotherapy. This open area is approximately 1100 m^2 and will be used to develop clinical support activities and patient facilities (waiting areas, exam rooms etc). The remaining beam rooms will be used for non-clinical aspects of the associated biomedical research program.

Accelerator needs (power supplies, electrical sub-station, etc.) are located in the open space at the top of figure 3 and in the area above the synchrotron. It is proposed that the facilities be located underground to minimize shielding requirements. Additional space will then be available at ground level for offices and research support area.

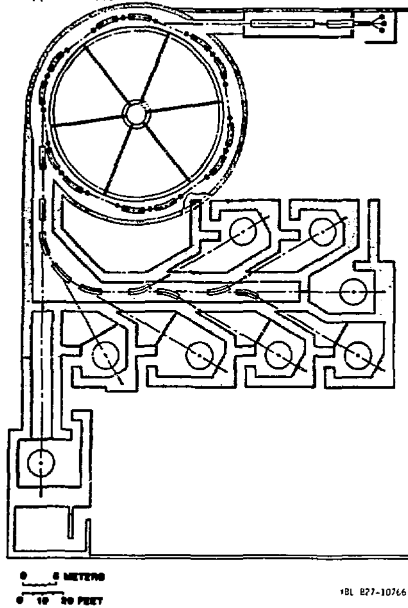

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Figure 3: Conceptual plan view of the medical accelerator and 8 beam rooms.

Conclusion

The success of the current heavy ion radiotherapy program at LBL plus the variety of treatment sites that require investigation have directed attention to the need for a dedicated heavy ion medical accelerator. The technology required to meet the medical requirements exists today. The present design effort is continuing and will lead to the submission of a specific construction proposal with complete cost estimates. It is projected that the construction effort will require 2 to 3 years to complete.

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