

## MEDICAL HEAVY ION ACCELERATOR PROPOSALS\*

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### Abstract

The potential efficacy of energetic, charged particles in the treatment of human disease has long been recognized. For several decades, accelerators designed primarily for research in nuclear and high energy physics have been adapted for biomedical research including radiotherapeutic treatment of human diseases such as pituitary disorders, cancer, and, more recently, arteriovascular malformations. The particles used in these treatments include pions, protons and heavier ions such as carbon, neon, silicon and argon. Maximum beam energies must be available to penetrate into an equivalent of about 30 cm of water, requiring treatment beams of 250 to 1000 MeV/nucleon. Certain special treatments of superficial melanoma, however, require that beam energies as low as 70 MeV/nucleon also be available. Intensities must be adequate to complete a 100 rad treatment fraction in about 1 minute. For most heavy ion treatments, this corresponds to  $10^7$ - $10^9$  ions/second at the patient. Because this research is best conducted in a dedicated, hospital-based facility, and because of the clinical need for ultra-high reliability, the construction of new and dedicated facilities has been proposed. Heavy ion accelerators can provide a variety of ions and energies, permitting treatment plans that exploit the properties of the ion best suited to each individual treatment, and that employ radioactive beams (such as  $^{11}\text{C}$  and  $^{19}\text{Ne}$ ) to precisely confirm the dose localization. The favored technical approach in these proposals utilizes a conventional, strong-focusing synchrotron capable of fast switching between ions and energies, and servicing multiple treatment rooms. Specialized techniques for shaping the dose to conform to irregularly-shaped target volumes, while simultaneously sparing surrounding, healthy tissue and critical structures, are employed in each treatment room, together with the sophisticated dosimetry necessary for verification, monitoring, and patient safety.

### Introduction

Specific clinical applications of relativistic heavy ion beams include the treatment of pituitary disorders, cancer and certain blood vessel abnormalities in the brain, such as arteriovascular malformations (AVM's). Using existing sources of charged particle beams, successful treatment procedures have been developed and demonstrated for certain pituitary disorders and certain cancers. The treatment of AVM's with charged particle beams, is an emerging field with a high initial success rate. Work is continuing, to develop additional treatment sites and procedures using beams ranging in mass from protons to argon. Non-clinical applications of these beams, include the study of radiation damage mechanisms in biological systems, and the evaluation of potential radiation hazards associated with extended manned space flight.

Interest in developing these research areas has been noted in a number of countries worldwide, including Canada, China, France, Germany, Japan, Sweden and the US. Proposals range from initiating a

biomedical arm on an existing accelerator research program, to the proposal of new accelerator facilities optimized for, and dedicated to, the pursuit of biomedical research and the related clinical programs. Proposals for dedicated heavy ion (mass 4 and higher) facilities are being pursued most actively in the US, at the Lawrence Berkeley Laboratory (LBL), and in Japan, at the National Institute for Radiological Sciences (NIRS). [1,2] There are, in addition, proposals for new light ion (mass 4 and lower) dedicated medical facilities, but these are not the subject of this paper.

A primary advantage of charged particle radiotherapy is that it offers a precise delivery of radiation to the tumour while, at the same time, minimizing the dose to surrounding healthy tissue or nearby critical structures. In addition, the biological effectiveness of heavy ion radiation, particularly in the Bragg peak, is higher per unit dose than for conventional x-rays treatments. Finally, heavy ion beams such as  $^{12}\text{C}$  and  $^{20}\text{Ne}$  can be efficiently transmuted to radioactive beams such as  $^{11}\text{C}$  and  $^{19}\text{Ne}$ , opening up the prospect of on-line diagnostics and treatment with particles whose actual stopping point within the patient can be clinically measured.

The case for the construction of new facilities is strengthened by the need for ultra-highly reliable radiation sources suitable for clinical work. Higher levels of reliability can doubtless be realized by the construction of new facilities dedicated to this type of research. Operation of the facility in a hospital setting or major medical center will provide improved patient care facilities, easier patient referral patterns, and a mechanism to transfer proven treatment modalities to the realm of community medicine, ensuring a direct impact on human health care.

### Performance Requirements

An emerging conclusion from ongoing heavy ion radiation studies is that no single ion can be identified as universally superior to all others. Rather, it appears advantageous to select the ion type with the properties best matched to each individual treatment. Fragmentation limits the clinical applications to beams of mass less than 40. In addition, care must be taken to ensure the efficient production and transport of radioactive beams for diagnostic and treatment purposes.

In order to make efficient use of the accelerator, it is necessary to minimize operating costs and to provide multiple treatment rooms. As it generally requires about 30 minutes to set up each patient for a 1 to 2 minute exposure, it is necessary to rapidly switch the beam with respect to treatment room, energy, and ion species. Consideration must be given also to the strong clinical need for vertical or oblique treatment ports. Persuasive arguments are advanced by radiotherapists for a vertical beam to permit treatment of a recumbent patient from above. Special techniques for the preparation, monitoring, and documentation of the treatment beams must also be provided. Treatment fields with diameters of 30 to 40 cm and a few percent uniformity are commonly required. In addition to spatial uniformity, it is

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also important that long uniform beam spills be available, free of RF or other time structure.

In order to treat deep-seated tumours, the beams must penetrate as much as 30 cm in tissue. This requirement sets the design energy in the range of 500 to 1000 MeV/amu for ions in the mass range 20 to 40. The treatment of superficial tumours, such as ocular melanoma, require that beams as low as 70 MeV/amu also be available. Reduced energies can be obtained by placement of absorbers in the external beam, but this leads to undesirable degradation in beam quality. This technique is useful for lighter ions, and small energy shifts, but it is preferable, and for the heavier ions essential, to provide the lower energies directly from the accelerator. In order to limit the treatment time to around 1 minute, intensities in the range of  $10^7$ - $10^9$  ions/second must be provided at the patient. Intensities for radioactive beams should be at least  $10^7$  ions/second.

The accelerator design must provide for the highest attainable standards of reliability - on the order of 95% or better. To achieve this, the components should be conservatively designed, and the overall system should be simple to operate, and have adequate intensity reserves. A sophisticated control system, with diagnostic and autotuning features that permit rapid switching among the ion species, energies, and beam use areas, is also needed. Simple machine operation, together with energy-efficient component design, are important aspects of minimizing operating costs.

#### Overview of Proposed Accelerators

Most designs aimed at satisfying these requirements emphasize the use of proven accelerator technology. The three most detailed designs, at LBL [1], NIRS [2] and the Univ. of Alberta (MARIA) [3] have, in fact, all arrived at a common approach: a conventional synchrotron, with a linac injector. With magnetic rigidities of 8-12 tesla-m, and with the requirements for fast switching, the incorporation of superconducting magnet technology does not appear attractive.

Table 1 summarizes the basic parameters for three of the most detailed Medical Accelerator designs. Though driven by a common set of requirements, the actual accelerator designs were developed independently. The MARIA design drew heavily from a worldwide base of accelerator expertise, and, unlike the others, is not a dedicated facility - rather one to be shared between biomedical and nuclear science interests. Nevertheless, the similarity of features and design parameters among all three designs is quite striking. The proposed sites for all three place them in a hospital or medical research environment.

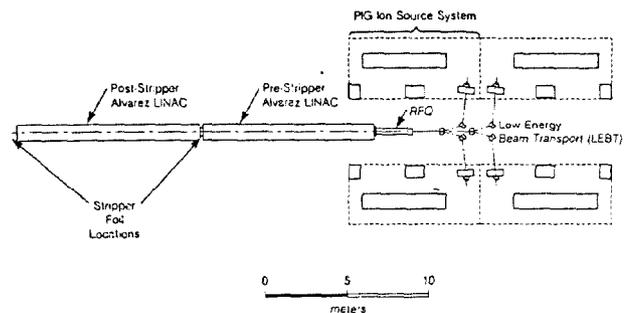
#### Injector

A schematic layout of the LBL injector design is shown in Figure 1. The PIG source/RFQ/Alvarez combination, particularly for low duty factor, heavy ion applications such as this, offers proven and reliable technology with flexibility to switch rapidly between ion species. The PIG produces high ion currents from both solid and gaseous source feeds. This layout shows possible expansion to as many as four ion sources, but only two are proposed, to satisfy the requirement for fast ion switching and to provide an added measure of redundancy. RFQ linacs, now operating successfully

Table 1: Parameter Summary for three Medical Accelerator Designs

	LBL	NIRS	MARIA	
Design ion	Si	Ar	Ar	
Injector Source Type	<=== Sputter PIG ===>			
Number	2	2	2	
RFQ Frequency	200	100	200	MHz
Q/A	0.14	0.14	0.15	
Input energy	8.4	10	10	keV/amu
Output energy	200	700	600	keV/amu
Length	2.24	5	8.15	m
Alvarez Linacs Frequency	200	100	200	MHz
Input energy	0.2	0.7	0.6	MeV/amu
Output energy	8	7.5	10	MeV/amu
No. of tanks	2	4	2	
Total length	21	26.4	23	m
Synchrotron Diameter	29	35.9	33.6	m
Input energy	8	7.5	10	MeV/amu
Max output energy	800	600	1000	MeV/amu
Repetition rate	2-4	2	.7-1	Hz
Duty factor	.2-.6	>.25	.2-.4	
No. of dipoles	12	24	16	
Max guide field	1.6	1.4	2.0	tesla
No. of quadrupoles	18	24	24	
No. of RF cavities	1	2	2	
Injection scheme	1 turn	multi-turn	multi-turn	
Biomedical Caves No. of beam rooms	8*	8	3	
Radioactive beam rooms	8*	1	3	
Horizontal ports	8*	8	2	
Oblique ports	0	0	2	
Vertical ports	1	2	1	

\* Initially 3, but expandable to 8



XBL 846-9048

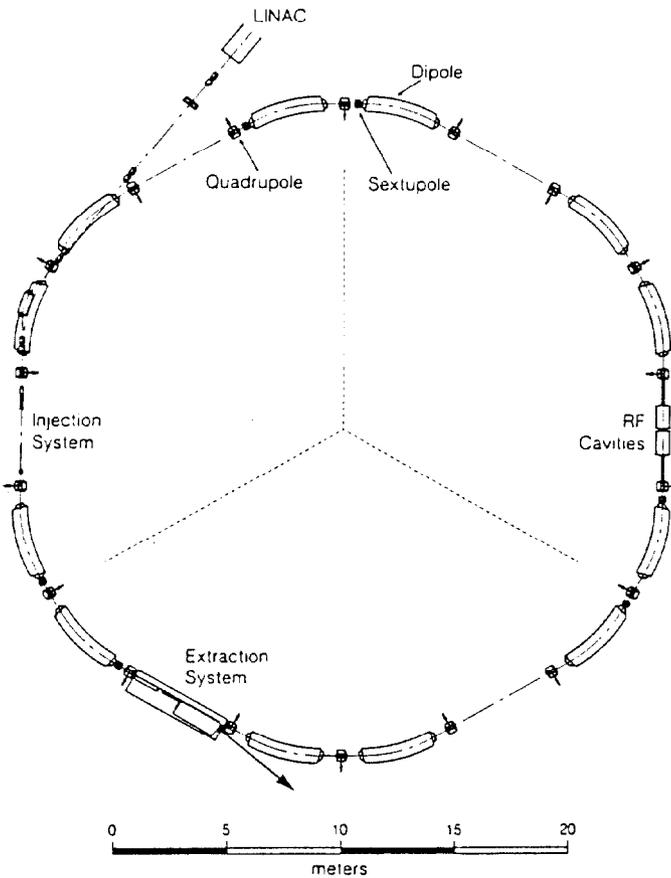
Fig 1 Layout of the injector from the LBL design study.

at several injectors used for production research, eliminate the need for Cockcroft Walton preaccelerators, and are particularly easy to maintain and operate. Furthermore, they permit the source to be maintained on a voltage platform less than 100 kV, greatly facilitating source access. The Alvarez linacs are of traditional design. Average power consumption is modest and reliability requirements are more easily satisfied because of the low duty factor, typically less than 0.1%. In all injector designs,

two foil strippers are used to raise the charge state. The injector output energy must be high enough that fully stripped ions can be efficiently produced at the final stripper. The required intensity for silicon at the exit of the injector in the LBL design is 26 pA. Higher intensities will be available for lighter ions.

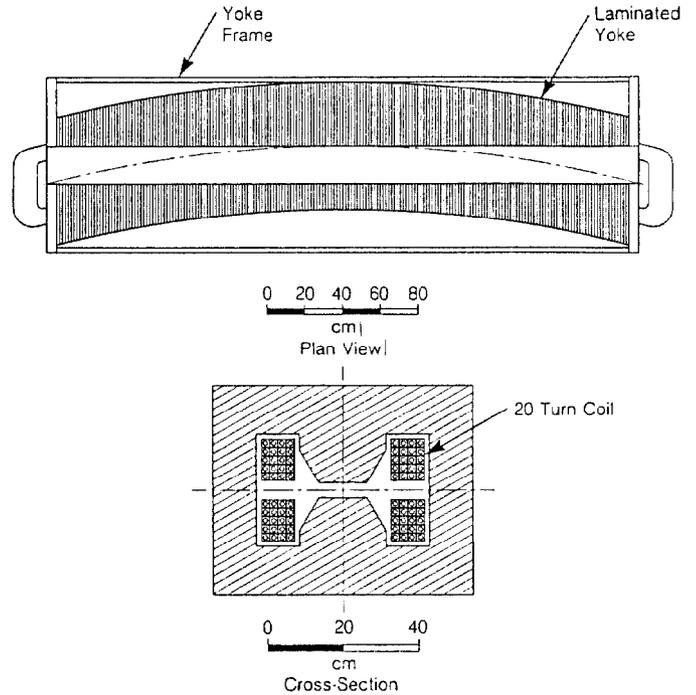
Synchrotron

The NIRS lattice utilizes 24 dipoles, each 1.5 m in length, and operating at a maximum of 1.4 tesla. There are also 24 quadrupole magnets each 0.3 m long, 12 long straight sections, and 2 RF cavities. The MARIA synchrotron is a virtual copy of the Saturne II ring. A layout of the ring developed in the LBL design study is shown in Figure 2. In this design injection is done vertically and in a single turn, using a septum magnet and ferrite-loaded fast kicker. The single turn injection simplifies the operation and fast switching of ion species, and leads to a compact, energy-efficient aperture requirement in the magnets. A 1.6 tesla guide field is provided in the curved dipole shown in Figure 3. It is of laminated construction, has a 30 degree bend angle, a 3.2 m length, a 4 cm gap, and a 10 cm aperture. Each dipole requires 46 kW at full excitation.



XBL 846-9008

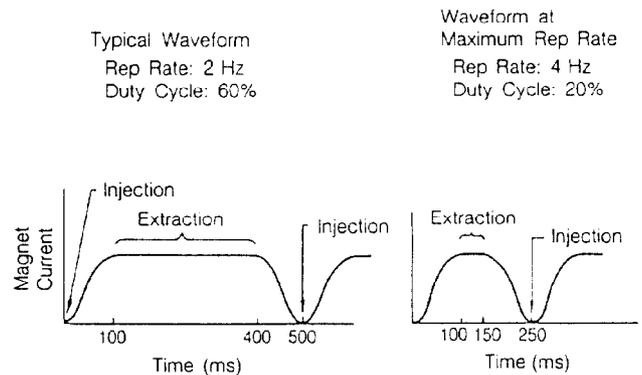
Fig. 2 Layout of the synchrotron ring from the LBL design study.



XBL 846-9006

Fig. 3 Dipole magnet from the LBL design study.

Typical waveforms are shown in Figure 4, illustrating 2 and 4 Hz operating modes of the LBL ring. In both modes the rate of rise is 16 tesla/second. In the 2 Hz mode, a duty factor of 60% is achieved. A slow, RF-off resonant extraction can be provided during flattop, avoiding high instantaneous dose rates at the patient and maintaining a uniform beam level suitable for dynamic methods of beam delivery, described below. Energy variability is achieved by programming the flattop for the desired beam energy. With adequate monitoring and controls, only a few pulses are required to change and verify the magnet excitation level. Resonant energy storage systems can be used to handle power requirements for the magnet system. The external Si ion intensity in the LBL design has been conservatively estimated as  $3 \times 10^8$  ions/second. Intensities for lighter ions are significantly higher.



XBL 846-9049

Fig. 4 Waveforms showing acceleration cycles for 2 and 4 Hz operation.

Beam Delivery

In certain clinical situations, it is desirable to provide treatments via vertical or oblique ports. The efficient manipulation of these rigid beams (up to 10 tesla-meters) in a vertical plane poses quite a challenge. However, since a full course of radiation treatments typically requires up to 20 or 30 separate fractions administered over a period of several weeks, it is not necessary to provide every port option in each treatment room. One of the more ambitious schemes, taken from the MARIA study, is represented in Figure 5. Horizontal ports are available in two of the three treatment rooms, one of which also has a vertically downward beam. The third room has a pair of  $\pm 45$  degree oblique ports.

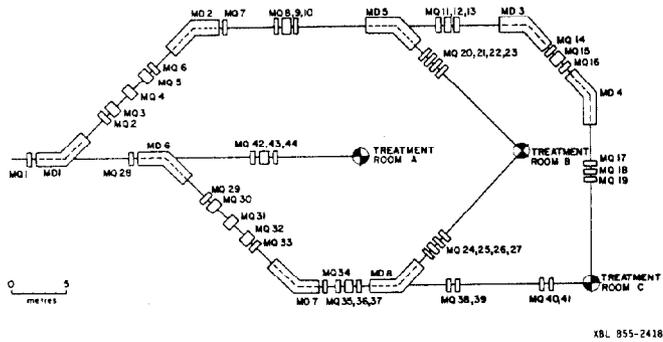


Fig. 5 Elevation view of transport system taken from the MARIA design study.

For some clinical applications, small beams are desirable, but for others, it is necessary to expand the beam to uniformly cover large areas. Circular fields of 30 and 40 cm diameters are frequently required, with a uniformity of a few percent. Magnetic deflection techniques can be used to achieve this using two orthogonally-deployed dipoles. Together with suitable range adjustment schemes, they can be programmed to scan the beam in a raster or circular pattern so the entire target volume receives the prescribed dose. These techniques place limits on the uniformity of the beam spill and on the duty factor. In addition, they require a drift distance to the patient of 5 or more meters.

Extensive and sophisticated equipment is needed in the therapy cave for patient treatments. This includes a wide variety of special filters or beam modification hardware, dosimetric apparatus, special purpose collimators, patient positioners and alignment devices. A typical setup of the Bevalac radiotherapy cave is shown in Figure 6.

Facilities Description

Figure 7 shows a layout for the LBL design, including the necessary radiation shielding. This

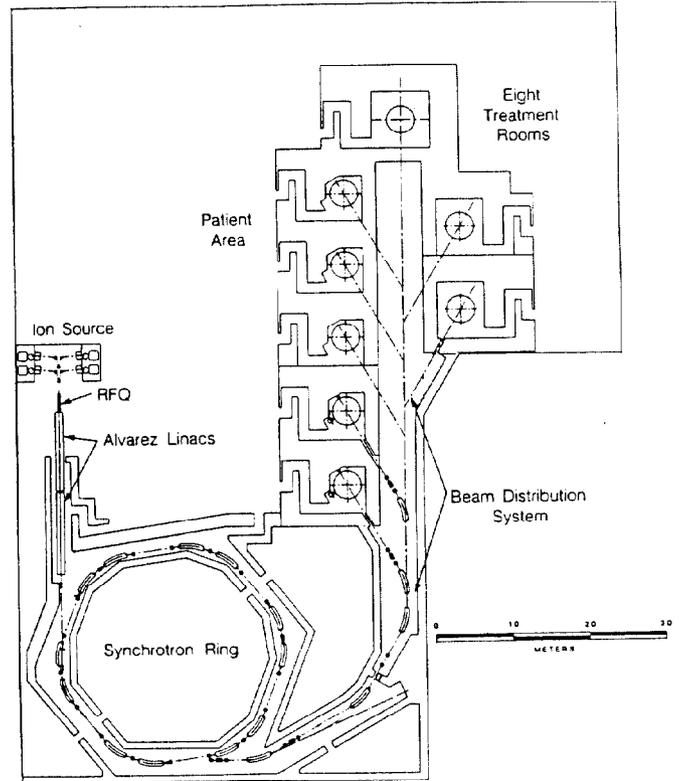


Fig. 7 Layout of the proposed LBL Medical Accelerator Facility.

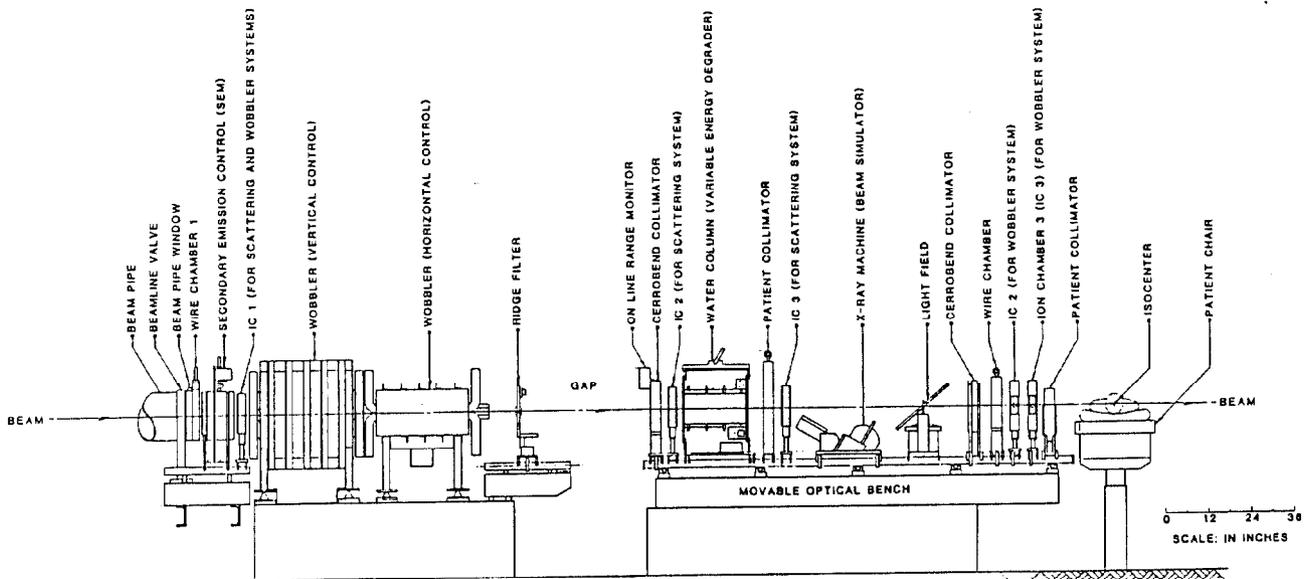


Fig. 6 Schematic view of the therapy bench setup in use at the Bevalac.

shielding is mostly poured-in-place concrete. It is proposed to pour for all eight beam rooms at the time of initial construction. Three rooms would be equipped for initial use. A vertical beam option is available for the end room. The caves and the beam transport optics are modular, minimizing the amount of retuning necessary to switch the beam between rooms. All controls are located in a single control room located on a mezzanine level above the patient area. Power supplies are located inside the ring and in the area just outside the synchrotron shielding. Total estimated power required for accelerator and beam delivery systems is about 2 MW.

Figure 8 shows the layout of the proposed NIRS facility. The area in the figure is about 9000 m<sup>2</sup>. A total of eight separately-shielded beam rooms are indicated. Note that in treatment rooms A and B, both horizontal and vertical beams are available. A special room is provided for radioactive beam work and radiographic diagnosis. Again there is an attempt to keep the patient activities separate from the operations and research staff.

#### Construction and Operating Costs

The direct costs of facilities like those proposed by LBL and NIRS is in the neighborhood of 75 M 1985 US dollars. This figure includes a multi story building structure that provides some 11,000 m<sup>2</sup> gross floor area. Nearly half of this total cost is in the building structure and conventional facilities, and special site considerations, or unusual architectural standards could substantially alter this figure. A construction period of 4 to 5 years is anticipated in both proposals.

For 2000 operating hours per year (40 hrs/week), the direct cost of running these accelerators in the United States would be around 1.4 M 1985 US dollars. Of this, about 40% is payroll expense, 30% is for power, and the remainder for miscellaneous supplies and expenses. For an additional 35% in operating costs, the accelerators could provide 4000 operating hours per year (80 hrs/week).

#### Concluding Remarks

None of the proposals discussed in this paper have been funded for construction at this time. However, proponents at NIRS and at LBL are actively pursuing plans to secure this funding in order that their research activities can be pursued on new facilities beginning in the early 1990's.

While much of the accelerator technology associated with these machines is not on the traditional frontiers of accelerator science, there are numerous interesting special problems and challenges in planning for these new facilities. These areas include control systems technology, reliability engineering, and the development of improved methods of treatment beam delivery.

#### Acknowledgments

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#### References

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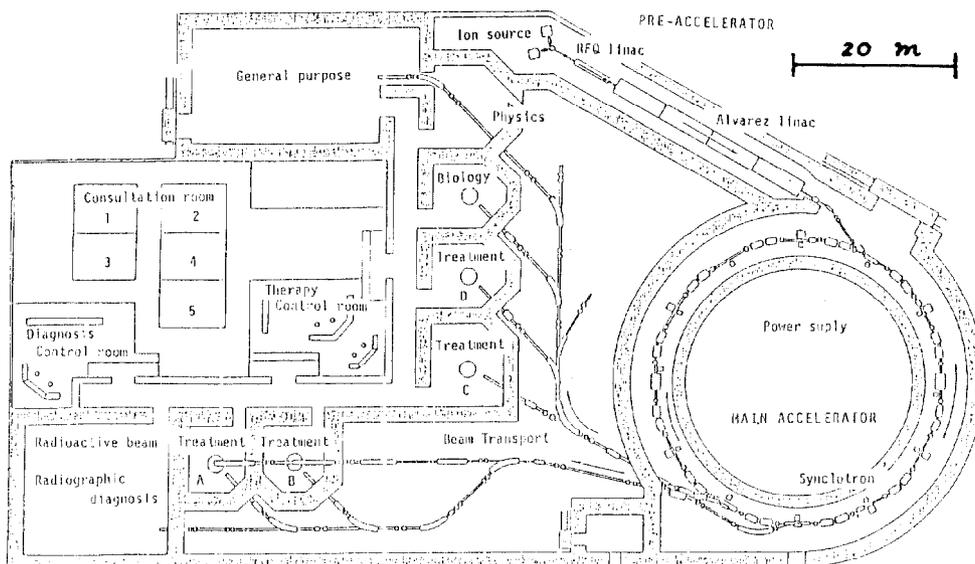


Fig. 8

Layout of the proposed NIRS Medical Accelerator Facility.