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PRESENT STATUS OF THE BEVALAC AND DESIGN
OUTLINE OF PROPOSED MEDICAL ACCELERATOR

R.A. Gough

March 1986

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PRESENT STATUS OF THE BEVALAC
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Abstract

The Bevalac currently supports a strong and diverse program of scientific research with beams of relativistic heavy ions in the Biomedical and Nuclear Sciences. These programs utilize ions throughout the Periodic Table that range in energy from a few MeV to 2 GeV/nucleon, including radioactive secondary beams, such as neon-19. This paper first provides a brief overview of the Bevalac, its present operational status and the accelerator improvement program, followed by a rationale for the proposed construction of a hospital-based modern synchrotron dedicated to applications in Biomedicine, including the radiotherapeutic treatment of cancer and other human disorders. An outline of the proposed design for the new machine is given, including a discussion of the design philosophy, a review of major accelerator components, and the expected performance and operating characteristics.

Introduction

Today's Bevalac is an accelerator complex that has evolved over the years from a successful high-energy proton facility in the 1950s and 1960s, to a versatile and unique facility for research with beams of relativistic heavy ions. Since the basic components were developed with technology now 30 years old, it has only been through a series of innovative upgrades that the facility has been transformed into one that has fostered the development of important new areas of heavy-ion research. In this process, the Bevalac has also provided a focus for significant accelerator development, including areas of interest to modern accelerator design. The Bevalac has provided beams for radiotherapy for approximately 10 years, permitting the development of an advanced Biomedical Facility and patient treatment program. In this paper, the Bevalac is described - its heavy-ion history and present status - and a brief overview is provided of the design for a new hospital-based facility, dedicated to the biomedical community.

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The Bevalac

The Bevalac Facility is comprised of three major accelerator components: the Bevatron, the SuperHILAC and the Local Injector. A weak focusing synchrotron, the Bevatron was originally designed to provide protons to over 6 GeV for experiments in high-energy physics. The SuperHILAC had its origins as an independent accelerator (the HILAC) of ions to mass 40, for research in nuclear physics and nuclear chemistry - notably research in the transuranic elements. What is now called the "Local Injector", because of its close proximity to the Bevatron, was originally used as a 20 MeV proton injector. The terms "Bevatron" and "Bevalac" are presently used to distinguish between operating modes that utilize the Local and the SuperHILAC injectors, respectively. Several major upgrades (over a 15 year period) to all of these accelerators have brought them from their original specifications to their present performance levels.

Brief History as Heavy Ion Accelerator

By 1970, the Bevatron had lost its pre-eminence as a high-energy proton facility, and interest gradually shifted toward developing its potential as a heavy-ion machine. In 1971, the Local Injector was used to provide modest intensities of nitrogen and carbon for acceleration in the Bevatron. This was accomplished by the addition of a PIG source to the Local Injector, and operating its 200 MHz, Alvarez linac tank in the $2\text{-}\beta\lambda$ mode. The Bevatron injection system and accelerating profiles had to accommodate a much lower injection energy of 5 MeV/nucleon.

About this time, the HILAC was undergoing major modifications to extend its useful range of intensities and masses, and was renamed the SuperHILAC. By the mid 1970s, motivated and funded from the need for heavier beams for Biomedical use, a transfer line was built to permit beams from the SuperHILAC to be transported 250 m (including a 50-m drop in elevation) for injection into the Bevatron, creating the Bevalac. By this time, the intensities of locally-injected carbon beams had improved, and were adequate for radiotherapy treatments, and interest in the heavier beams from the SuperHILAC from the research community was high. Competition for beam time was strong, and the scheduling of the accelerator was already becoming a real challenge.

In 1980 the Third Injector was added to the SuperHILAC, extending its mass range to uranium, and improving intensities of the heavier-mass beams. It was not until 1982, however, when the addition of a cryogenic vacuum liner to the Bevatron made possible for the first time the full acceleration of ions heavier than iron to relativistic energies.⁽¹⁾ In 1985, an upgrade to the Local Injector was completed extending its mass range to $A=40$. This capability was added to provide the beams needed for the radiotherapy program independent of the SuperHILAC, with an increased overall flexibility in servicing the experimental program. Much of the technology developed for the Local Injector upgrade is directly applicable to the proposed Medical Accelerator, and will be described in greater detail below.

Overview of Present Bevalac Facility

An overall plan view of the Bevalac Facility is shown in Figure 1. The main components are the SuperHILAC and Local Injectors, together with the transfer line coupling them to the Bevatron, the Bevatron itself, and the Experimental Hall which includes the Biomedical Facilities.

The SuperHILAC consists of two 70 MHz Alvarez linacs, each followed by foil strippers and capable of accelerating beams to 1.2 and 8.5 MeV/nucleon respectively. Three independent injectors, seen in Figure 1 as EVE, ADAM, and ABEL, provide ions in the low, middle, and heavy mass ranges respectively. The EVE injector, used for beams up to mass 40, consists of a PIG ion source and a 750 kV Cockcroft Walton high-voltage set; the ADAM injector, used up to mass about 140, consists of a sputter-ion PIG source and a 2 MV pressurized dynamitron; and the Third Injector, ABEL, capable of providing all ions but optimized for the heaviest masses, consists of a dual-head, sputter-ion PIG source, and a 750 kV Cockcroft Walton followed by a Wideröe linac and fomblin stripper. The SuperHILAC is pulsed at 36 Hz, and a sophisticated control system permits pulse-to-pulse time-sharing of the machine. For example, one possible operating mode provides 2 pulses per second of one ion for injection in the Bevatron, 32 pulses per second of a second ion for use in the low energy (8.5 MeV/nucleon) experimental area, and 2 pulses per second of a third ion

Fig. 1 The Bevalac.

for a parasitic low energy user. An advanced, high-current "MEVVA" source is being added to the Third Injector as part of an ongoing project, discussed below, to increase the intensities.

The Local Injector is used to provide beams up to mass 40. It consists of a sputter-ion PIG source, a radiofrequency quadrupole (RFQ) linac, and 2 Alvarez linacs. Injected at 8.4 keV/nucleon, the RFQ accelerates beams with charge-to-mass ratios $Q/A \geq 1/7$, to an energy of 200 keV/nucleon. An Alvarez linac continues the acceleration to 0.8 MeV/nucleon, where a foil stripper raises Q/A to a value $\geq 1/3$. The second Alvarez linac then provides the final acceleration to 5 MeV/nucleon, where a second foil stripper is employed to fully strip the beam prior to injection into the Bevatron. All 3 linacs operate at 200 MHz and provide two 800- μ s pulses per second.

Built in the 1950s, the Bevatron is a weak-focusing synchrotron with four quadrant sections and four straight or tangent sections. The beam is guided through each of the quadrant sections by a single, large dipole magnet. The Bevatron can be switched in a few seconds to receive beam from either the SuperHILAC or the Local Injector. With a maximum rigidity of 19.2 Tesla-meters, it accelerates beams with $Q/A = 1/2$ to 2.1 GeV/nucleon, and uranium to 0.96 GeV/nucleon. A large-aperture, drift-tube-type RF system, located in one of the tangent tanks, provides the acceleration. It is a two-gap system, with a peak voltage of 25 kV per gap, and a frequency swing of 10:1. It operates on first harmonic. The Bevatron is pulsed 15 cycles per minute, and uses a slow resonant extraction to provide long uniform beam spills. Magnet power is supplied from 2 large motor generator sets each connected to a 61 metric-ton flywheel. The large (30 cm x 122 cm) magnet aperture has a cryogenic liner to maintain an average operating pressure of $< 10^{-10}$ Torr. This pressure is necessary to ensure reasonable survival of the heavier beams which must be accelerated as partially-stripped ions.

There are two well-equipped experimental areas at the Bevalac: a low energy experimental area located at the exit end of the SuperHILAC for experiments with all ions up to an energy of 8.5 MeV/nucleon; and a high-energy experimental hall near the Bevatron, for all ions up to the maximum rigidity of 19.2 Tesla-meters. This area incorporates the

Biomedical Facility, fully equipped with sophisticated beam-modulating devices, instrumentation, patient positioners, and control systems.

Overview of the Present Operations Program

The Bevalac currently provides approximately 3000 on-target hours of beam time each year, a limit set by budget considerations. This is divided in the ratio of two-thirds for Nuclear Science, and one-third for the Biomedical Program. A typical operating year runs continuously from the beginning of the fiscal year (Oct. 1) until the beginning of the summer. This provides a measure of operational continuity, essential for the patient treatments. At present, these treatments are done during the day shifts, Tuesday through Friday. About two hours are spent at the beginning of each day for dosimetry. In this mode the high-energy beam is typically shared between radiotherapy and biology. The radiotherapy beam is provided from the Local Injector. Nuclear Science running is done primarily at night and over the weekends.

A list of developed beams available at the Bevalac is given in Table 1. The ions that have been extensively developed reflect the demand from the experimental program. Use of standard ions representative of a particular mass range is encouraged, to avoid unnecessary time for machine development.

The Accelerator Improvement Program

The accelerator improvement efforts at the Bevalac have played a key role in maintaining the facility in the forefront of heavy-ion research. Many of these developments have not only been beneficial to the Bevalac experimental programs, but also have influenced our thinking on the design of the proposed Medical Accelerator. A brief discussion of selected developments is given here.

A major upgrade of the Local Injector was recently completed⁽²⁾ and, in 1985, was successfully placed on-line.⁽³⁾ Figure 2 shows a schematic layout of its major elements. The RFQ linac⁽⁴⁾ used in this project serves as a prototype for the Medical Accelerator injector. It is a loop-driven, four-vane structure, azimuthally stabilized with vane coupling rings (VCRs). Because of the VCRs, the structure can be assembled and tuned very efficiently, and dynamic frequency control can be maintained with a single tuning loop. Much of the design work

Table 1: Bevalac partical inventory list, August 1985.

Ion	Atomic Weight A	Atomic Number Z	Accel. Charge	Max. Energy MeV/amu	Ext. Intensity particles/pulse
Hydrogen	1	1	1	4900	2×10^9
(molecular)	2	1	1	2100	1×10^9
Deuterons	2	1	1	2100	$1 \times 10^{5*}$
Helium	3	2	2	3010	3×10^8
	4	2	2	2100	1×10^{10}
Boron	11	5	5	1840	1×10^9
Carbon	12	6	6	2100	5×10^9
Nitrogen	14	7	7	2100	1×10^5
Oxygen	16	8	8	2100	6×10^9
Fluorine	19	9	9	1950	1×10^8
Neon	20	10	10	2100	1×10^{10}
Magnesium	24	12	12	2100	1×10^7
Aluminum	27	13	13	2000	5×10^8
Silicon	28	14	14	2100	8×10^8
Argon	40	18	18	1815	1×10^9
Calcium	40	20	20	2100	4×10^7
	48	20	20	1640	1×10^7
Manganese	55	25	25	1840	$1 \times 10^{6*}$
Iron	56	26	24	1700	2×10^8
			16	1050	$5 \times 10^{7*}$
Nickel	58	28	26	1810	1×10^6
Krypton	84	36	33	1510	$1 \times 10^{7*}$
Niobium	93	41	35	1420	2×10^6
			23	770	8×10^7
Xenon	129	54	45	1280	5×10^5
	132	54	45	1240	1×10^5
	136	54	45	1180	3×10^6
Lanthanum	139	57	52	1410	1×10^5
			48	1260	4×10^7
			32	690	8×10^7
			29	587	6×10^7
Holmium	165	67	54	1170	2×10^5
Gold	197	79	61	1080	1×10^5
			37	490	1×10^7
			35	450	5×10^6
			11	50	1×10^5
Uranium	238	92	68	960	1×10^6
			40	410	1×10^7

* Low intensities are at experimenters' requests; no maximization has been done.

Fig. 2 Schematic layout of the Local Injector.

for the Alvarez linacs is also directly applicable to the Medical Accelerator design, such as the pulsed drift tube quadrupole magnets. A summary of linac parameters is given in Table 2.

Table 2: Summary of local injector linac parameters.

	RFQ	Alvarez	
		Tank 1	Tank 2
Frequency (MHz)	200	200	200
Length (meters)	2.24	3.53	12.9
Q/A	0.143	0.143	0.350
Energy in (keV/amu)	8.4	200	800
Energy out (MeV/amu)	0.200	0.800	5.0
Peak power (kW)	150	600	2200
Duty factor	0.0016	0.0016	0.0016
Oper. mode	-	2 β λ	2 β λ
No. of cells	346	38	50

About 90% of the operation to date has been with neon, reflecting the present needs of the Radiotherapy program as it moves into Phase III neon trials. Consequently, only the neon beam is well-developed and studied at this time. Intensities readily available on a routine basis, are more than ample to satisfy the present radiotherapy needs. A list of all ions that have been run, together with intensity data taken directly from the operations log, is given in Table 3. The source intensities quoted are measured in the low energy beam transport line

Table 3: Summary of local injector operations, Feb. 1986.

	Charge State from PIG		Observed Intensities	
	(Q)	(Q/A)	Analyzed near the Source (pA)	Accelerated in the Bevatron (Part/pulse)
Mol. hydrogen	1+	0.500	700	9×10^9
Helium-4	1+	0.250	1160	4×10^{10}
	1+	0.250	2000	-
Carbon-12	2+	0.167	250	1×10^9
	2+	0.167	450	-
Oxygen-16	3+	0.188	270	5×10^9
Neon-20	3+	0.150	250	9×10^9
	3+	0.150	334	-
Neon-20	4+	0.200	140	4×10^9
Neon-22 *	4+	0.181	35	5×10^8
Silicon-28	4+	0.143	100	-

* Natural isotopic enrichment 9%.

after the analyzing magnet, using a deep, electron-suppressed Faraday cup. Intensity measurements at the linac exit are difficult to interpret because there is no provision for adequate charge-state separation. A more useful datum, given in the last column in Table 3, is the induction electrode measurement of beam captured and accelerated in the Bevatron.

The PIG source lifetime has been 30 days or more of continuous operation. A rebuilt source can be substituted and be back on-line in about an hour. Overall injector reliability is already approaching 95%, with most of the failures associated with the RF components borrowed from the early operation of the linac. Stripper-foil lifetimes appear to be on the order of several months.

Improvements presently underway at the SuperHILAC are expected to provide significant increases in the uranium beam intensity. These will be accomplished primarily through an enhancement of uranium production and transport in the ABEL injector: incorporation of a metal vapor vacuum arc (MEVVA) high-current ion source⁽⁵⁾, new beam line elements, and improved pumping speed. The recently-developed MEVVA source is capable of producing 100 mA of U^{5+} with good emittance. Limitations imposed by the transport of these intense beams, and in the space-charge limits of the Wideröe and Prestripper tanks will determine the ultimate increase in beam intensity translated to the user areas. A fivefold increase over present beam levels is expected. Another factor of two is expected from other SuperHILAC improvements, bringing the U^{+40} intensity at the SuperHILAC exit to 0.1 pA.

Future improvements to the Bevalac Facility are also under study. The most far-reaching of these plans involves a proposal, still in a very preliminary stage, to replace the Bevatron with a modern, strong-focusing synchrotron with a resulting intensity increase of 150 for light masses ($A=20$) to 800 for uranium. The Bevatron would be partially dismantled and the new accelerator ring placed inside the present Bevatron shielding. This limits the circumference to approximately 135 m, and the rigidity to 18 Tesla-meters. The cycling rate for this proposed ring is variable from 0.2 to 1 Hz. Improved beam quality for fixed target experiments, and a fast extraction capability

are two additional goals. The fast-extraction opens the way for a storage ring, capable of storing and cooling both primary and secondary (radioactive) beams from the new accelerator ring. A 9 Tesla-meter storage ring has been studied (capable of receiving U^{92+} - accelerated as U^{40+} to 370 MeV/nucleon in the accelerator ring and stripped) with provision to reinject into the synchrotron, permitting uranium beams to be further accelerated to 1.3 GeV/nucleon. The storage ring could also be injected directly from the SuperHILAC, and operated in a stretcher mode for high-duty-factor, low-energy experiments. A major feature of this plan is to maximum the use of the existing infrastructure such as shielding and utilities. In particular, the SuperHILAC and the Local Injector would remain as injectors and the existing experimental facilities, including the Biomedical area would remain intact. The plan provides capabilities similar to those at the SIS-18 project now underway at GSI.⁽⁶⁾ At this time, such a modernization effort for the Bevatron Facility is under study, but the details of the plan are still preliminary.

Rationale for a New Dedicated Medical Accelerator

Without the Bevalac, the development of heavy ion Biomedical studies could not have taken place. However, for a number of reasons, the Bevalac is not the ideal environment to continue this work. To best understand why, it is useful to first examine the requirements desired in the new facility. These are summarized as follows:

- Safety
- Reliability
- Minimum staffing and power costs
- Flexibility and fast switching among ion species, energies, and target areas
- Efficient production and delivery of radioactive beams
- Some beams with long range (>30 cm)
- Efficient system for preparation and delivery of treatment beam
- Generous duty factor, and uniform spill
- Hospital-based environment, clinical ambiance
- High patient throughput $\Rightarrow$ multiple treatment rooms
- Dedication to the needs of a cohesive, biomedical program

While some of these requirements must be (and are) satisfied with the present Bevalac, and still others could be addressed with a modern Bevatron replacement discussed above, clearly all of the items can be satisfied only with the construction of a new, dedicated and hospital-based facility. Even a modern synchrotron, if designed for the higher intensities and heavier ions sought by the nuclear science community, cannot be operated as effectively as a machine tailored to those requirements specific to the Biomedical Program. A dedicated machine will have lower operating costs and will eliminate scheduling difficulties in sharing among user groups with diverse needs. Siting the facility near a hospital provides ancillary facilities needed for patient care, facilitates the patient referral process, and provides a mechanism to transfer the medical techniques to a community-based system of human health care.

Outline of Proposed Medical Accelerator

A detailed summary of the LBL Medical Accelerator design is available as LBL PUB 5122.⁽⁷⁾ Only a brief outline of the design is given here.

Design Philosophy and Technical Approach

In order to provide an accelerator with clinical standards of reliability, that can be operated simply with a minimum operations and maintenance staff in a hospital environment, a design was developed using proven accelerator technology. The strong-focusing synchrotron, together with a high-performance control system satisfies the above requirements. It also provides for rapid switching of the ion and energy delivered to a particular target area. The traditional injector for the synchrotron is the linac. It also satisfies the need for flexibility and, together with pulsed PIG source technology, readily provides the intensities required at injection to ensure efficient patient treatment. The recent developments in RFQ technology make the linac option even more attractive. The reliability and performance of all these subsystems is well established, eliminating the need for R&D, and leading to a design with predictable performance and costs. Table 4 gives an analysis of the projected intensities for selected ions. The technical choices made in the LBL Medical Accelerator design are strikingly similar to those reflected in the NIRS design.⁽⁸⁾

Table 4: Projected intensities of selected ions
in the medical accelerator.

	Helium	Carbon	Neon	Silicon	Argon	
Source performance						
Elec. current	5000	5000	5000	2000	1680	µA
Charge state	1	2	3	4	6	
Particle current	5000	2500	1667	500	280	µA
Intensity	3.1E+16	1.6E+16	1.0E+16	3.1E+15	1.7E+15	p/sec
Injector transmission table						
LEBT	0.75	0.75	0.75	0.75	0.75	
RFQ	0.8	0.8	0.8	0.8	0.8	
Prestripper	0.9	0.9	0.9	0.9	0.9	
Stripper 1	0.5	0.5	0.45	0.4	0.3	
Poststripper	0.75	0.75	0.75	0.75	0.75	
Stripper 2	1	1	0.9	0.8	0.5	
MEBT	0.75	0.75	0.75	0.75	0.75	
Injector performance						
Elec. current	1519	2278	2050	680	230	µA
Charge state	2	6	10	14	18	
Particle current	759	380	205	49	13	µA
Intensity	4.7E+15	2.4E+15	1.3E+15	3.0E+14	8.0E+13	p/sec
Synchrotron injection						
Inj. window	2.34	2.34	2.34	2.34	2.34	µsec
Inj. efficiency	0.9	0.9	0.9	0.9	0.9	
Circulating beam	1.0E+10	5.0E+09	2.7E+09	6.4E+08	1.7E+08	<u>particle</u> pulse
Synchrotron transmission table						
RF capture	0.5	0.5	0.5	0.5	0.5	
Acceleration	0.95	0.95	0.95	0.95	0.95	
Cycling rate	4	4	4	4	4	Hz
Extraction	0.75	0.75	0.75	0.75	0.75	
External beam	1.4E+10	7.1E+09	3.8E+09	9.1E+08	2.4E+08	p/sec
Beam to target						
Delivery transmission	0.4	0.4	0.4	0.4	0.4	
Int. on target	5.7E+09	2.8E+09	1.5E+09	3.6E+08	9.6E+07	p/sec
Dose rate on target	1422	3792	4095	1456	735	<u>Rad-1</u> min
Source performance for						
600 Rad-1/min.....	2110	791	733	824	1371	µA
Source performance						
demonstrated.....	5000	5000	5000	2000	1680	µA

Overview of Medical Accelerator Components

The injection system provides the synchrotron with 8 MeV/nucleon, fully-stripped ions up through mass 40. While space is reserved to accommodate as many as four independent PIG-source systems, two are proposed at the time of initial construction. A different ion from each source can thus be quickly switched on-line. A low energy beam transport system (LEBT) matches the beam from each source and injects an RFQ linac with a low-charge-state ion such as $^{28}\text{Si}^{4+}$ with $Q/A=0.14$. The RFQ accelerates the beam to 200 keV/nucleon and injects an Alvarez linac that continues the acceleration to 1750 keV/nucleon. At this energy, a foil stripper raises the charge state to $Q/A=0.35$, and a second Alvarez accelerates the beam to 8 MeV/nucleon. The ions are then fully stripped by a second foil stripper and injected vertically into the synchrotron in a single turn. The PIG source design is taken from the dual-head ABEL source now in use at the SuperHILAC. The RFQ is identical in design to the one now in service at the Bevatron Local Injector. The Alvarez linacs are each about 11 m in length, operate at 200 MHz, and require about 1 MW of peak power with a duty factor of $\ll 0.001$. The first Alvarez operates in the $2\beta\lambda$ mode, and the second on the fundamental. Much of the technology in the Alvarez linacs is similar to that used in the Local Injector.

The synchrotron accelerates fully-stripped beams from 8 to a maximum of 800 MeV/nucleon and has a circumference of 91.8 m. It can be operated at 2 or 4 Hz cycling rates with duty factors of 60% and 20% respectively. A separated-function lattice is chosen for ease of tuning. It has three superperiods and six 4.7-m-long straight sections. It utilizes 12 curved, 30° dipole magnets, each 3.2 m in length, and 18 quadrupoles, each 0.4 m in length. The dipoles have a 3.8-cm gap, a 9-cm aperture, and a maximum guide field of 1.6 Tesla. The quadrupoles have a good-field aperture of 10 cm and a maximum gradient of 7.65 T/m. A single-turn injection scheme is chosen to simplify operation and to minimize the magnetic volume and hence power requirements. The principal injection elements are a magnetic septum and a fast ferrite-loaded kicker. Resonant extraction techniques are used to provide uniform, RF-off spills. The extraction system includes an electrostatic septum and two magnetic septa. A ferrite-

tuned RF cavity with a 7:1 frequency swing, located in one of the six long straight sections provides the acceleration. It operates on second harmonic. Vacuum requirements in the ring are in the low 10^{-7} Torr range.

The high-energy beam transport (HEBT) system emphasizes modularity and ease of tuning.⁽⁹⁾ The magnets in the HEBT are of the same general design as those used in the accelerating ring. A minimum number of elements need to be retuned when switching between target rooms. The modularity also simplifies future expansion for additional beam lines. In addition to the user area target rooms, a separate, fully-instrumented tuneup beam line is provided to permit the operator to preview the beam and verify its properties. Provision is made for secondary (radioactive) beam generation and transport to all target areas. A vertical beam line option to at least one of the treatment bays is also included. Within each treatment bay, a sophisticated, well-instrumented medical beam line is provided, including advanced beam-scanning devices.

A high-performance accelerator control system is extremely important in achieving the goals for a medical accelerator. The system developed in the LBL design is characterized by the use of many dedicated computers each performing a definite, fixed function. It is a system of distributed intelligence in which software effort - historically a dominating cost component in accelerator control systems - is kept to a minimum. High-level control functions, such as accelerator modelling, is done with a high-performance minicomputer. Control and monitoring of the actual patient delivery systems is also accomplished with minicomputers, taking advantage of many years of control systems development at the Bevalac Biomedical Facility. Separate and completely independent controls for each treatment bay are recommended for maintainability and safety. Communications between the minicomputers and the rest of the control system is easily accommodated on a network such as Ethernet.

Facilities Overview

Figure 3 shows the layout of the complete facility. It is proposed that 8 separately-shielded target areas be provided although

Fig. 3 Layout of the proposed Medical Accelerator facility.

only three are to be made operational at the time of initial construction. Three target areas for non-clinical research use are separated from the patient area, where a hospital-like ambiance is maintained. Approximately 7000 m² is provided on the accelerator level, with additional space available on a second level.

Based on input specifications from LBL, a complete study of the conventional facilities was undertaken by the Bechtel Corporation of San Francisco. Also participating in this effort was the Merritt Peralta Medical Center in Oakland, who has offered a site on their campus - a 15-minute drive from LBL. This study includes the building, radiation shielding, foundations, electrical power distribution,

and all aspects of conventional construction. The installed power specification for the accelerator and treatment facilities is 2590 kVA. This figure is based on accelerating argon to 800 MeV/nucleon and an 80% power factor.

Projected Construction and Operating Costs

Based on a three-year construction schedule, plus an additional year for planning activities, direct costs for both the technical components and the conventional facilities are estimated at 75 million 1986 US dollars. The distribution of these costs is given in Figure 4. The direct cost - including salaries, electrical power and all supplies and other expenses - of operating the facility in the United States today, is estimated at 1.5 million 1986 US dollars for 2000 beam-hours/year. The hourly cost of providing beam is thus \$750. However, in two-shift operation, 5 days/week, our analysis shows that 4000 beam hours/year can be provided for \$500 per hour. Furthermore, if the facility were operated 24 hours/day for 5 days/week, then 6000 hours/year would be available at a cost of only \$420 per hour. Of the total operating cost, approximately 30% is required for the purchase of firm electrical power.

Conclusions

The Bevalac continues to provide relativistic, heavy-ion beams from protons to uranium for experiments in Nuclear and Biomedical Science. However, the scope of the experimental program requires a degree of flexibility that is both technically difficult and comparatively costly to provide with the Bevalac. Furthermore, it is less than ideal to conduct patient treatments in a multidisciplinary research-laboratory environment located far from hospital-support services. It is a clear conclusion of the LBL Medical Accelerator design effort that the goals established for a new dedicated machine can be achieved with proven technology at predictable costs. Present activities are focused on continuing support of the Biomedical Program at the Bevalac, and on further development of advanced techniques of beam delivery, appropriate for use at a new facility.

Facilities Total

Fig. 4 Pie chart showing distribution of construction costs.

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