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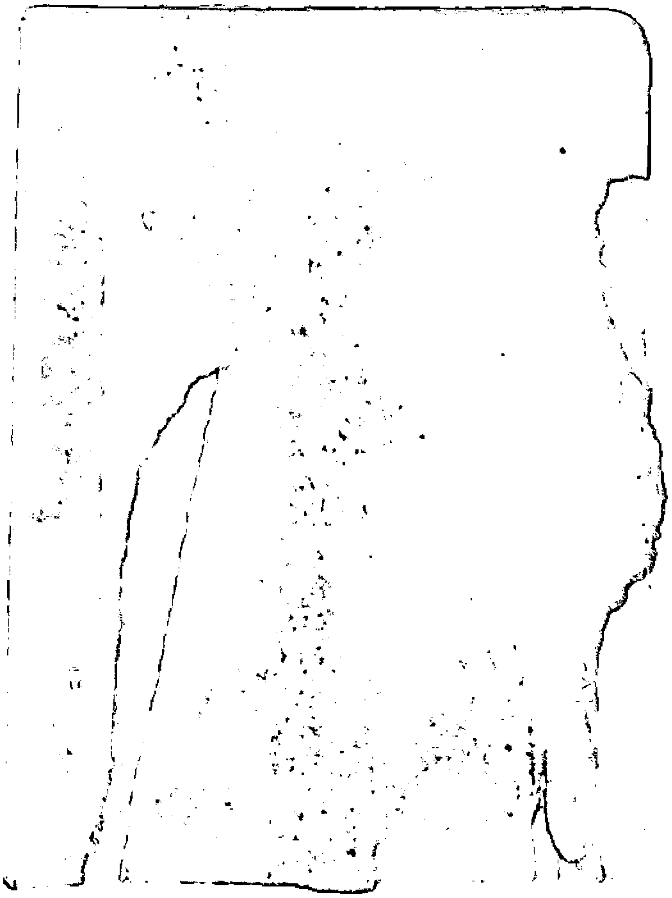

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ABSTRACT

Improvements are planned for the Berkeley Heavy Ion Linear Accelerator which will make possible the acceleration of all elements from hydrogen to uranium to 7.5 MeV/nucleon. The improved system will consist of a 2.7 MV dc injector, a new 11 meter-long prestripper linac and the existing 27 meter long poststripper linac which will be extended to 37 meters. Baffles in the latter portion of this cavity will separate it into individually excited segments to provide completely variable energy from 3 to 7.5 MeV/nucleon.

To provide the lighter heavy ion beams, at energies acceptable for biological research and medical therapy, a 25 meter diameter rapid cycling alternating gradient synchrotron is proposed. With this machine fully stripped ions from the Hilac with $M \leq 20$ can be accelerated to energies up to 500 MeV/nucleon. Details of the synchrotron design will closely follow those developed for the Omnitron and a prototype of the Omnitron accelerating resonator will be used.

INTRODUCTION

The maximum energy range of present interest for heavy ions used in nuclear chemistry is determined by the energy required for the formation of compound nuclei, 5-7 MeV/nucleon. The principle source of these ions during the past eleven years at Berkeley has been the Heavy Ion Linear Accelerator (HILAC). This accelerator produces a maximum energy of 10 MeV/nucleon and consists of a dc injector, 2 Alvarez-type RF cavities with provision for ion stripping at 1 MeV/nucleon between the two cavities. The injection energy, particle charge-to-mass ratios in both cavities, and the stripping velocity were designed for the efficient acceleration of ions with mass up to 20 (neon).

Over the years improvements have been made to the Hilac to increase its duty factor from the original 3% to 80% for the light ions and 20% for the heaviest ions. Higher electric gradients in the two cavities have been made possible by additions to the RF amplifier system, so that ions up to argon ($M=40$) can be accelerated.

During the past few years a substantially increased interest has developed in the ultraheavy ions ($M \leq 240$) in this energy range. The principle problem of producing these heavier ions is the difficulty in removing enough electrons to produce a sufficiently high charge-to-mass ratio for their efficient acceleration. The conventional cold-cathode PIG ion source is capable of removing electrons with ionization potentials up to about 150 volts, and, for the ultraheavy ions, this corresponds to a charge-to-mass ratio of about 0.05, the minimum acceptable ratio for the existing Hilac is 0.140, so that this accelerator cannot be used for ultraheavy ions without major alterations.

In addition to the nuclear chemistry requirement for the extremely heavy ions in the low energy range, biophysic studies at the Hilac, combined with high promising results achieved with medium energy charged particle medical therapy, have created a high degree of interest in the use of heavy ions ($A=40$) in this field. The general requirement for these ions is the ability to produce a precisely controlled dose in a precisely defined region of tissue at depths ranging up to 15 cm. These requirements, when transformed into beam specifications, demand a high quality beam with a continuously variable and precisely controlled energy. The maximum energy is determined as that required to produce a 10 cm range in tissue for argon ions, approximately 400 MeV/nucleon.

In 1965, the author, with A. Ghiorso and B. Smith, conceived a system capable of accelerating acceptable intensities of all elements to maximum energies varying from .3 GeV/nucleon for uranium to 1.4 GeV for protons. This system, the Omnitron,[1] consisted of a 3 MV Cockcroft-Walton injector, a rapid-cycling alternating gradient synchrotron, and a storage ring. It satisfied all of the requirements of the nuclear chemistry and the biology and medical research groups at Berkeley. Proposals for the construction of the accelerator were submitted to the Atomic Energy Commission, and included in its proposed budget, on three successive years. Due to its high cost, however, the project has not been approved.

The accelerator system described here is designed to satisfy the minimum requirements of the research groups at a minimum cost. These minimum requirements are shown in Table I.

The proposed system consists of an improved Hilac (Super-Hilac) designed to provide beams for the nuclear chemistry research, and a rapid-cycling synchrotron to accelerate beams from the Hilac to energies acceptable for biomedical research.

The necessity for the use of as much of the existing Hilac components as possible, imposes a considerable restriction on the design parameters of the proposed Super-Hilac. The synchrotron design is also restricted by the requirement that the components developed for the Omnitron be used. These consist of the accelerating resonator designed to operate at 50 kV and cover the frequency range 7.5 to 33 MHz, the fast extraction system, and the guide magnets and their power supply.

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*This work was done under the auspices of the U. S. Atomic Energy Commission.

Table I. Heavy Ion Beam Requirements

Nuclear Chemistry		
Mass number	1 through 238	
Energy range	3 - 7.5 MeV/nucleon	
Energy resolution	0.5%	
Intensity	10^{11} particle/sec heaviest ion.	
Duty factor	1.5	
Biology and Medicine		
Mass number	1 through 20	
Energy range	50 - 400 MeV/nucleon	
Energy resolution	0.5%	
Intensity	10^{12} particle/sec	M=1
	10^{11}	M=4
	10^{10}	M=6-20
Duty factor	None	

PRESENT HILAC

The existing Hilac is shown in plan as Fig. 1. It consists of a 500 kV Cockcroft-Walton Injector, a 4.5 m grid-focused Alvarez linac, an ion stripping station, and a 27 m magnetic quadrupole-focused Alvarez linac. The prestripper linac was designed to operate with a maximum electric gradient of 1.6 MV/m and, at this gradient, accepts particles with a charge-to-mass ratio (ϵ) of 0.15 (e.g., neon-20 +3) at an injection energy of 0.076 MeV/n. The particles are accelerated to 1 MeV/n in this cavity, then passed through a stripper (either foil or gas) which increases their charge-to-mass ratio to a minimum of 0.30. With a maximum electric gradient which varies linearly from 1.45 MV/m at the entrance to 1.9 MV/n at the exit, the poststripper linac will accelerate these particles to a maximum of 10.1 MeV/n.

The grid-focused prestripper linac operates with a synchronous phase angle of about 12 degrees and, with bunching, accepts about 0.3 of the particles. The fraction of the particles that appears in a single charge state after stripping, varies from 0.3 for the lighter ions to 0.2 for argon-40. The poststripper linac transmits all of this beam. In addition to these losses, the duty factor of the accelerator is limited to 0.2 for the heaviest ions and to 0.8 for the lightest. The product of transmission and duty factor thus varies from about 3×10^{-2} to 2.5×10^{-4} from the lightest to heaviest particles. Beams of practically all elements up to argon-40 have been accelerated, with intensities varying from 10^{8}/sec for metallic elements to greater than 10^{13}/sec for the lighter gaseous elements.

The poststripper cavity can be made to accelerate partial energy beams by reducing the linear increase in the electric gradient along the cavity. The synchronous phase angle is thus reduced to zero at some point; particles are accelerated to this point and drift the remaining length without energy gain. Particles drop out of phase in three or four adjacent gaps so that the beam exits the accelerator with three or four discrete energies. By precise tuning of the electric gradients, the injection phasing, and the quadrupole lenses, up to 30% of the injected beam can be made to exit the accelerator with a single energy which can range from 0.25 to 0.75 of the design full energy. The energy distribution of the partial energy beams varies from about 70 to 110 keV/n FWHM, as compared to 50 keV/n for the full energy beam, and its RF structure is attenuated.

The proposed improvements to this accelerator, and the proposed synchrotron are described below:

ION SOURCE AND INJECTOR

The Hilac ion source is a PIG discharge operating in a magnetic field of about 4500 gauss which also serves as a charge-state analyzer. The beam is extracted, transverse to the magnetic field, with 18 kV from a 0.125 cm x 2.0 cm long slit. The source can be operated either with a cold cathode with electrons produced by secondary emission, or with a plasma-heated, thermally-emitting cathode. The cold cathode operates with a high arc voltage and is used to enhance the production of the higher charge states, whereas the hot cathode is used to produce intense beams of low charge state ions. Single charge beams in excess of 10^{15} particles/second have been produced with this source, for the light ions (to mass 20) with $\epsilon \geq 0.15$ and for the heavier (to mass 130) ions with $\epsilon \geq 0.05$.

A variation of the cold cathode source has been developed in which a support gas is used to sputter metals from the surface of the anode into the plasma. The source produces moderate (10^{13}/second) beams of metal ions in the lower charge states with $\epsilon \cong 0.05$.

Although only preliminary work has been carried out with the ultraheavy ions, investigations with mercury-200 indicate that acceptable beams greater than 10^{14}/second of +9's ($\epsilon = 0.045$) can be produced with the cold cathode source. Comparable beams of uranium-238 +10's ($\epsilon = 0.042$) are expected using UF_6, and since this charge-to-mass ratio is consistent with the metallic ion beam produced with the sputter-ion source, we have chosen this value as the minimum to be accepted in the proposed accelerator.

The accelerator is to operate in two modes, producing beams of the ultraheavy ions for nuclear chemistry research and serving as an injector for the biomedical synchrotron. Since the ion source injector is the least reliable component in the system, multiple injectors should be provided. We have recently built for the Hilac, but not yet installed, a high current, 750 kV Cockcroft-Walton injector and it is desirable that this unit be used for the improved system. The lighter ions (to neon-20) to be used by the biomedical research groups can be produced in quantity with $\epsilon \geq 0.15$. The use of the 750 kV unit as an injector for these ions specifies the injection energy of the linac section, T_1 = 0.1125keV/nucleon. This injection energy in turn specifies the injector voltage required for the ultraheavy ions, $T_i/\epsilon_{min} = 2.7$ MV.

When the ions are extracted from the Hilac source with a constant 18 kV and accelerated to 0.076 keV/n (the Hilac injection energy) approximately 90% of all beams with $0.1 \leq \epsilon \leq 0.25$, appear within a phase area of 5 cm-mr. in both planes. No increase in this value is anticipated for the heavier, low charge-to-mass ions. The acceptance requirements of the new prestripper linac, at the higher injection energy, is thus about 4π cm-mr in both planes.

The 2.7 MV injector will be similar to that proposed for the Omnitron,[1] for which preliminary design exist. It consists of a shunt fed 100 kc Cockcroft-Walton generator utilizing silicon diodes and operating in a 250 PSI N-CO_2 atmosphere.

ALVAREZ CAVITIES

The linear accelerator system is to operate similarly to the existing Hilac with an intermediate energy stripping station. The requirement that the existing RF amplifiers and the 27 meter cavity be used, restricts the frequency of the proposed system to 70 ± 7 MHz, and the position of the long cavity within the existing building restricts the length of the prestripper cavity to about 11 meters. Additional length also will be required for the poststripper cavity to accelerate the low charge state ions to the required energy, so that the existing experimental area must be moved. The designs details of the quadrupole, drift tubes, and hanger system for all cavities will closely follow those developed for the Hilac.[2]

The prestripper cavity will operate at 1 $\beta\lambda$ and utilize magnetic quadrupole focusing in the NNSS configuration throughout. With the entrance magnetic gradients at 14.5 kG/cm and the electric gradient varying from 1.7 MV/m at the entrance to 2.1 MV/m at the exit, the system will accept 7π cm-mr and accelerate ions with $\epsilon = 0.042$ from 0.1125 MeV/nucleon to 0.750 MeV/nucleon. The magnetic gradients is that achieved in dc magnets presently under test, and the electric gradient is consistent with operating experience on the existing Hilac prestripper cavity.

The poststripper linac system must be designed to operate with injection energy of 0.720 MeV/n and to accept particles with a charge-to-mass ratio corresponding to the mean charge after stripping of the highest Z element to be accelerated. At 750 MeV/nucleon and using a foil stripper, it is estimated that the mean stripped charge state of uranium-238 is +36, corresponding to $\epsilon = 0.15$. The poststripper linac system has been designed to operate with this minimum charge-to-mass ratio.

This charge-to-mass ratio is advantageous in that it allows the acceleration of the light ions (to neon-20) without the use of a stripper and the attendant beam loss. For the ions to be injected into the synchrotron, therefore, the only major beam loss will be the longitudinal phase acceptance of the prestripper cavity. In addition, all ions up to 130 (iodine) can be stripped with gas, with no limitation on beam intensity. The ions which must be stripped with a foil will be limited in intensity not only by ion source output but also by foil lifetime.

The presently used technique described above for the production of variable energy from the poststripper cavity requires time consuming precision tuning, and results in a relatively poor quality beam with a significant loss in intensity. For the improved system, four individually excited cavities will be provided to allow for variable energy in the range 3 to 7.5 MeV/nucleon. Investigation indicates that by adjustment of the injection phase and the RF amplitude a continuously variable energy gain from zero to the designed gain can be obtained with these cavities, without serious degradation of the beam quality. To cover the entire required energy range from 3 MeV/nucleon, successive cavities will be excited, with the final excited cavity acting as a vernier. We are also investigating a short cavity at the high energy end of the accelerator, consisting of two or three gaps operating at as high an electric gradient as possible, to be used as a buncher or to provide further vernier control. A plan view of the improved accelerator is shown in Fig. 2.

R. F. SYSTEM

The two existing RF cavities are excited by six RCA type 6949 beam power triodes, one driven amplifier on the prestripper cavity, with one driven and five tuned-plate-tuned grid amplifiers on the poststripper. The amplifiers are powered by a single 25 kV, 7 MW power supply and are plate modulated to produce RF amplitude regulation to within 0.1%.

A fast motor driven tuning loop in the prestripper cavity adjusts its resonant frequency to track the poststripper cavity, which is allowed to vary (with temperature). Phasing between the two cavities is held to within about 2 degrees by a 10 MHz band width electronic regulator operating on the driven amplifiers of both cavities.

Each of the amplifiers is capable of delivering 750 kW peak, 250 kW average, at 70 MHz. The system is designed to operate with a duty factor varying from about 80% to a minimum of 20% at the peak electric gradient (minimum charge-to-mass ratio).

Since this system operates satisfactorily, it will be used on the new accelerator with minimum modification. A new 2.5 mW plate power supply will be required to power the prestripper cavity, which requires grossly different plate voltages than the poststripper cavities for some ions. The new accelerator will require eleven amplifiers, three on the prestripper, four on the long section of the poststripper and one each for the four incremental energy cavities. The small cavities will be designed to operate with about 500 kW peak RF power, so that the tubes which deteriorated with age can be rotated into these positions.

SYNCHROTRON GUIDE RING

A preliminary layout of the 26 meter diameter synchrotron ring is shown as Fig. 3. It consists of 48 magnets, in 4 superperiods each consisting of 12 magnets arranged in a modified FOFOD configuration. The arrangement provides one 2 meter and five one meter straight sections in each superperiod. The long straight sections will be used for injection, extraction and the RF resonator. The shorter sections will contain trim magnets and beam monitoring equipment.

The magnet design will be that developed for the Omnitron with the magnet profile adjusted to 3.20/meter and the apertures to 11.4 cm and 2.3 cm for the F magnets and 8.4 x 3.3 cm for the D magnets. The magnets will operate with a 22.5 Hz biased sinewave between 1.20 and 10 kg. Figure 4 shows a prototype of this magnet.

ACCELERATING SYSTEM

Figure 5 shows the prototype Omnitron accelerating resonator system.[3] The unit operates with a maximum gap voltage of 50 kV and a frequency swing from 7.5 to 33 MHz. For the biomedical synchrotron, the cycling rate, the guide ring radius and the total energy gain, have been adjusted so that this single resonator is capable of providing the required gain/turn.

Particles are injected with a velocity of 0.128 c and accelerated to a maximum of 0.72 c corresponding to orbit frequencies of 0.37 and 2.13 MHz, a frequency range of 5.6:1. The RF system will operate on the 12th harmonic from 5.6 to 32.2 requiring an additional low frequency resonator covering the range 5.6 to 7.5 MHz.

INJECTION AND EXTRACTION

The injection system will consist of a conventional electrostatic inflector. Adequate magnet aperture has been provided to make possible multiturn injection up to a maximum of 10 turns.

Extraction will be accomplished with a fast ferrite magnet system similar to that designed for the Omnitron. In this system the beam is deflected approximately 5 mr by pulsed magnets in one straight section, past a 1.6 kG dc thin septum magnet in the next straight section.

To reduce the rise time requirement of the fast magnet, it is planned to bunch the high energy beam at a subharmonic using the low frequency resonator system. Using this scheme, a magnet with a rise time of 0.1 μsec and a duration of 1 μsec will extract all of the beam at energies ranging from 50 to 400 MeV/nucleon.

Slow extraction from the synchrotron is not planned.

VACUUM SYSTEM

At present it is planned to accelerate only fully stripped ions at injection energies of 7.5 MeV/nucleon. The charge exchange problem is therefore limited to recombination only, and for the ions to $Z = 15$, cross sections for this process are less than 10^{-16} cm^2 and decreasing with velocity. Losses are, therefore, expected only during the early part of the acceleration cycle.

The vacuum chamber will consist of ceramic tubing within the magnets and stainless steel elsewhere. The system will be completely heliarc welded using the techniques developed for the Omnitron.[4] The system will be protected against catastrophic failure in the Hilac or the experimental areas by fast-acting valves and acoustical baffles.

Twelve ion pumps will be provided with provision made for an additional twelve. With an initial outgassing at 100°C the system is expected to operate at mean pressures of about 10^{-8} torr. At this pressure it is estimated that less than 10% of the ions with Z up to 10 will be lost due to recombination.

PLANT FACILITIES

The improvements to the Hilac will require an addition to the existing building to accommodate the injector system which must be moved to provide space for the expanded prestripper cavity. The experimental cave system will be moved to allow for extension of the poststripper cavity, and enlarged to accommodate an expanded research program.

Figure 2 shows one of the several possible plans for synchrotron ring and the Biomedical Experimental Area. The ring enclosure consists of a 8-ft diameter tunnel bored into a steep hill adjacent to the existing building. The beam is brought out into a highbay experimental area, which must be added.

Adequate input power and cooling utilities are available for the improvements to the Hilac; only minor rerouting within the building will be required. For the synchrotron an additional 3 MW power and 2.5 MW of cooling will be required.

PERFORMANCE

Losses in the Hilac system will be limited to longitudinal phase acceptance and to stripper loss, the latter varying from a factor of four for argon-40 to 10 for the heaviest elements. For the ions requiring the highest electric gradients in either of the two cavities, the duty factor will be limited to 30%.

Beam intensities will be decreased by these losses and limited either by the ion source output or by the stripper foil, which must be used for elements heavier than $M = 130$. For reasonable foil life, incident intensities must be limited to approximately 5×10^{12} per second.

Ion source output of the required charge-to-mass ratio, as noted above, varies from about 6×10^{15}/second for the lighter gaseous elements to 10^{12} for the heavier low vapor pressure elements. Limited experience with the sputter ion source indicates the possibility of producing currents varying from 10^{14} for the light elements to 10^{10} for the moderately heavy elements.

Peak intensities of about 6×10^{15}/second of all ions up to mass 20 are expected. At least fifty percent of the ions injected into the synchrotron should be captured and accelerated, resulting in average intensities of about 5×10^{11}

from this machine. Acceleration of argon-40 will require minimum pressure in the synchrotron and decreased intensities are expected due to charge exchange.

REFERENCES

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3. Bob H. Smith, IEEE Transactions on Nuclear Science, June 1967, page. 250.
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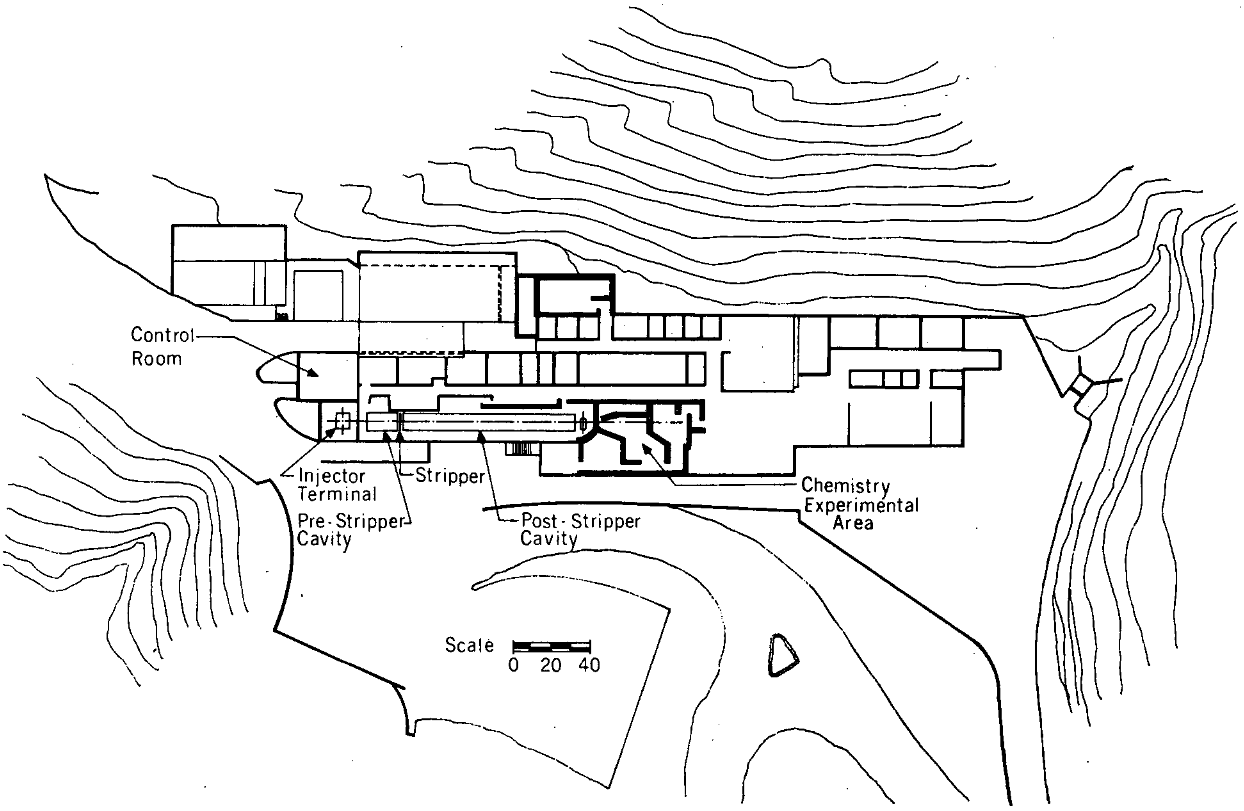


Fig. 1 Plan of existing Hilac facility.

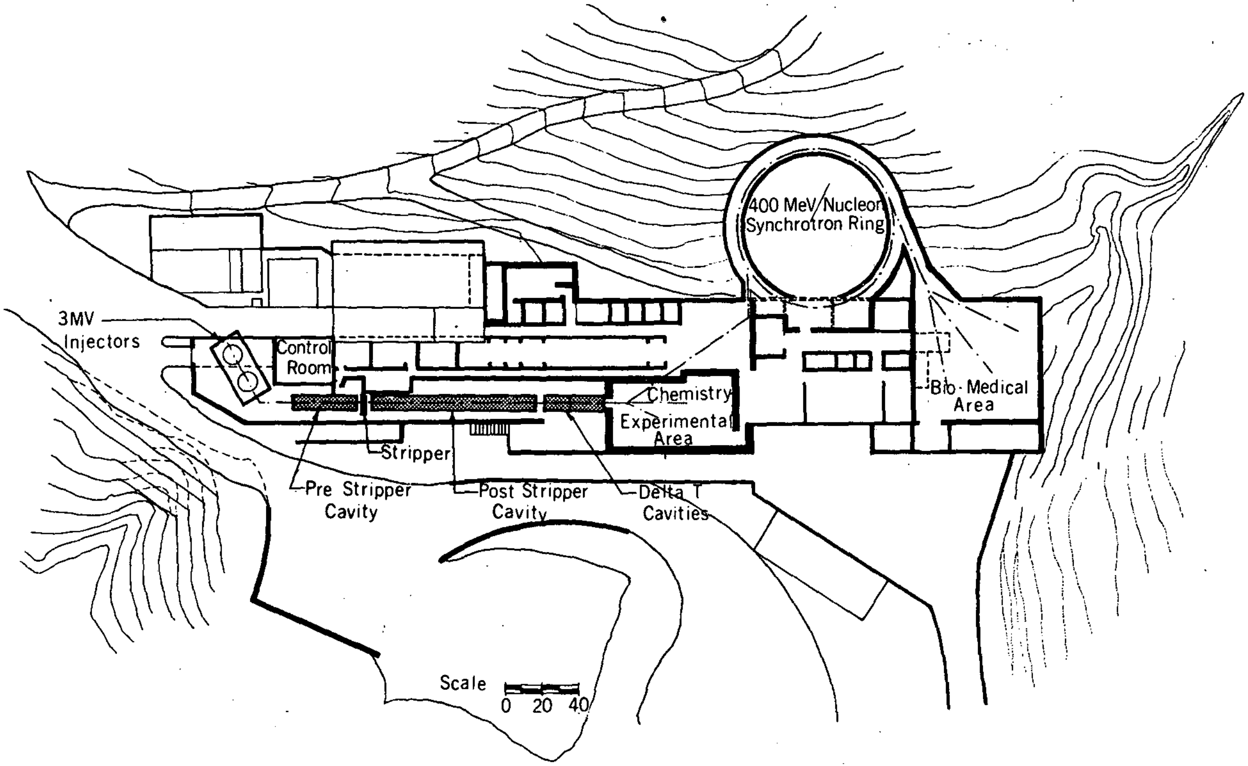


Fig. 2 Plan of proposed Hilac and biomedical synchrotron facility.

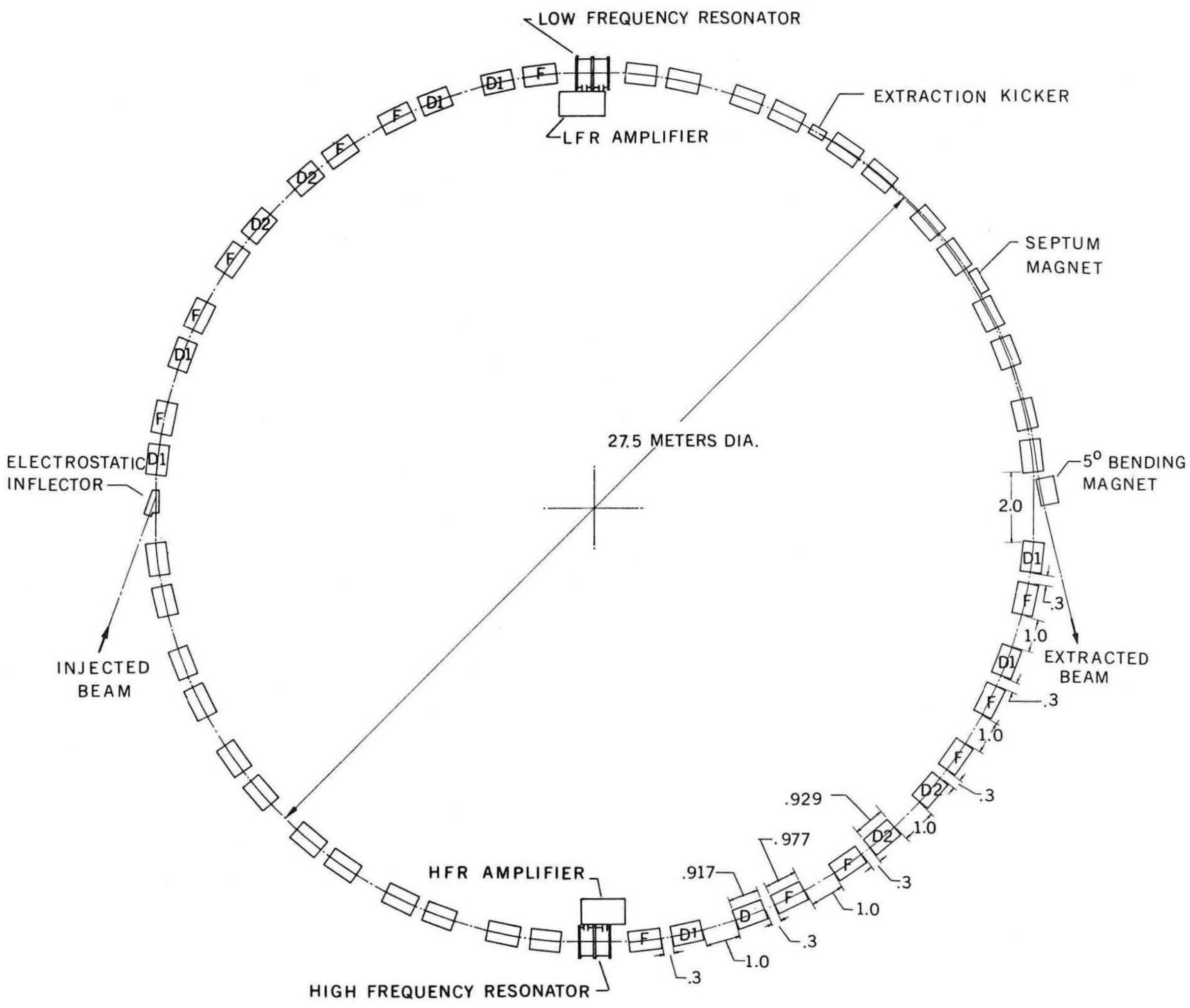
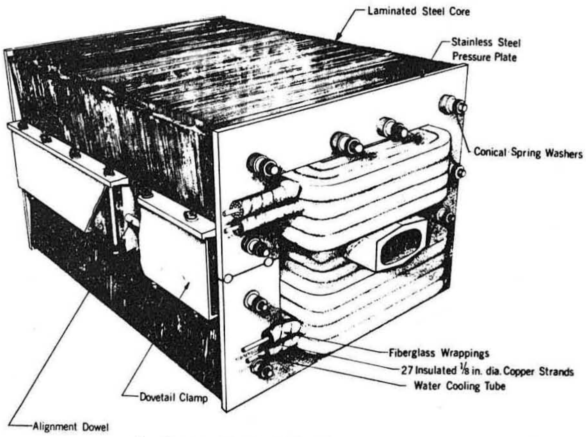


Fig. 3 400 MEV/NUCLEON SYNCHROTRON



Synchrotron Gradient Magnet

Fig. 4

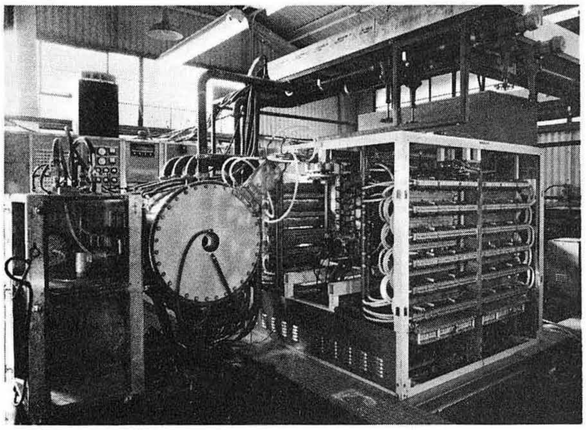


Fig. 5 Synchrotron accelerating resonator 7.5-33 MHz.

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