The Los Alamos Meson Physics Facility

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Ten years ago a group at Los Alamos, headed by Dr. Louis Rosen, proposed to the A.E.C. to build a meson factory at Los Alamos based on a linear accelerator capable of producing 1 mA of protons at 800 MeV energy. The facility was promised to be national in character and to have the capabilities to accommodate many users in both basic research and in practical applications.

Construction of the facility began early in 1968, and on June 9, 1972, it produced its first beam at full energy, about 3 weeks ahead of schedule, and at a construction cost of $ 57 million; only a few percent above that estimated many years before. Figure 1 shows the facility as it appears today.

The heart of the facility is an accelerator composed of three distinct stages, the first being an almost-conventional Cockcroft Walton injector, followed by a not-so-conventional drift-tube linac which accelerates the beam to 100 MeV for injection into a completely unconventional third stage, the side-coupled linac which accelerates the beam to its final energy of 800 MeV. The accelerator is about to one kilometer long and is designed to accelerate both H^{+} and H^{-} ions simultaneously to any energy in the range from 200 to 800 MeV. These beams are separated in the switchyard and sent to different experimental areas to support a wide variety of experimental programs. The linac is pulsed 120 times per second for a period of 500 microseconds, giving a macro duty factor of 6%. Plans call for extending the pulse length to 1000 microseconds in the future to produce a 12% duty factor. The peak current of the H^+ beam during the pulse is 17 mA, which for the 6% duty cycle, yields an average current of 1 mA. The peak currents of the H^- beam is limited by the ion source to several hundred microamperes.

Figure 2 puts these parameters in their proper perspective on the world-wide inventory of research accelerators. One can see that the beam intensities from existing accelerators in the medium energy physics range (100-1000 MeV) are in the vicinity of 0.1 microamperes. The four meson factories under construction represent increases in this important quantity by factors of 1000 to 10,000. It must be clear that any facility that pushes a frontier as important as intensity forward by a factor of 10,000 will find many important applications.

Figure 3 identifies the scientific purposes of LAMPF, as envisioned some years ago. Today, the more than 150 proposals for use of this facility reflect interest in every area depicted here. The diagram illustrates our dedication to the thesis that this facility shall be harnessed to both the intellectual and material welfare of society.

The facility is shown again in Fig. 4. The large building in the foreground, which incidentally is 25 meters high, is the main meson experimental area. The smaller building behind it is the nuclear physics experimental area, and the dome of earth covers a high resolution magnetic spectrometer for nuclear structure work. The building to the left of the accelerator is the Operations building, which houses, among other things, the computer control system.

The town of Los Alamos can be seen in the background. Both the town and our facility are on a plateau at an elevation of 2,200 meters above sea level. Behind Los Alamos are the Jemez Mountains which form the eastern rim of one of the largest volcanic craters in the world (20 km in diameter).

Accelerator

The creation of the beam and the first stage of acceleration take place in one of three Cockcroft Walton injector installations as shown in Fig. 5. The power supply is designed for 1 MV at sea level. We operate the set at 750 kV. The power supply is connected to the ion source terminal by the large horizontal resistor. The ion source is mounted at the high voltage end of a small ceramic column located inside the large polystyrene cylinder and the 15 voltage-dividing rings. The platform surrounded by the yellow railing can be raised and lowered to provide convenient access to the ion source dome. Electrical power for equipment in the dome is supplied by a generator in the dome driven by an insulated shaft from below. Control of the equipment in the dome is provided by a dozen open-air optical light links.

Figure 6 shows the system which transports the beam from the ion sources to the linac. We have two injectors that are operational at the present time and one in the planning stage. The injector to the left of this picture produces an ordinary proton beam (H^+) and the injector to the right of the picture produces beams of H^- ions (proton surrounded by two electrons). The injector still in the planning stage will produce beams of polarized H^- ions. The facility is designed with the capability to accelerate the H^+ beam and either (but not both) of the H^- beams simultaneously, each with the full beam duty factors.

The drift-tube linac is shown in Fig. 7. It accelerates the beam from 0.75 MeV to 100 MeV in a distance of 62 meters. The linac is divided into 4 tanks, each of which resonate at 201.25 MHz. The tanks consist of a copper-clad steel cylinder loaded with drift tubes, each of which are suspended from the top of the cylinder by a single vertical stem.

The first tank, shown in Fig. 8, is short and accelerates the beam to 5 MeV with a peak power consumption of about 500 kW. Each of the remainding 3 tanks add about 30 MeV of energy in a distance of 20 meters for an investment of 3 MW of peak power.

Figure 9 shows a view inside the third tank. The post couplers extending horizontally from the wall of the tank, serve stabilize the field distributions in the tank. Each of them are a tuned resonator which remain unexcited when the field distributions are proper, and which become excited for all other distributions. The enhanced field stability comes from the peculiar property that the excited resonators set up fields which cause the power to flow in the direction to correct the field distribution. The fields in these tanks are several hundred times more stable than they would be without the stabilizing system.

ginning of the side-coupled linac. Beam at this point has an energy of 100 MeV. The region between the two linacs is called the transition region and performs many functions important to the performance of the facility. Perhaps the most interesting function and one which adds much complexity to the region is the separation and recombination of the plus and minus beams in such a way that they can continue to be accelerated beyond 100 MeV simultaneously. Without this function, half of our schedulable beam time would be lost.

The problem is the following. The plus and minus components of the beam are accelerated through the drift-tube linac on opposite halves of the RF cycle. They leave the drift-tube linac separated by one-half cycle. This half cycle at 201.25 MHz corresponds to two full cycle at 805 MHz. If the side-coupled linac, which operates at 805 MHz, is phased to accelerate the positive beam, the negative beam will come at the same phase (2 cycles later) and because of the difference in charge, will be decelerated instead of accelerated.

One of the few solutions to this problem is to separate the two beams and pass one of them through a path that is 8 cm longer than the other, creating a "delay line" or "sidetrack" for the beam. This is, in fact, what we do. A plan view of the region is shown in Fig. 11. We normally pass the negative beam through the side track. Figure 12 shows the degree of complexity and compactness required to implement this valuable scheme.

Figure 13 shows the side-coupled linac, which extends for about 700 meters. This portion of the linac is divided into 44 modules for the purpose of power sources, control and instrumentation. Each module is about 16 meters long, and consumes about 1 MW of peak power at 805 MHz. The power is supplied by 44 klystrons capable of a peak power output of 1.25 MW.

The accelerating structure is shown in Fig. 14, and is composed of accelerating cavities, coupling cavities and bridging cavities. The structure operates in a standing-wave mode where the accelerating cavities are highly excited, and the coupling cavities are virtually unexcited. Here, again, the unexited cavity becomes excited for improper field distributions, and in effect, forces the field distributions to the design values. A cutaway section of an actual copper structure is shown in Fig. 15.

Control System

A facility as large and complex as this one, with its potential of putting beams on many targets simultaneously, must have a powerful and versatile control system. The concept of computer control was adopted from the very beginning of the project. A relatively large amount of money and manpower went into its realization, and has resulted in the most powerful and versatile control system in the accelerator world today. The system is based on a single large computer that is connected to the controls for the entire accelerator, to the operator consoles and to its normal peripheral hardware as shown in Fig. 16.

The central control room is shown in Fig. 17. At present, there are two control consoles; a third console is in preparation. Each console is a general purpose display and interaction interface. Any control function can be preformed equally well from any of the control consoles. Controls are initiated by the operator through use of the keyboard, push buttons, knobs, trackball and lightpen.

The center portion of the console (Fig. 18) features a graphic scope, a character scope (color T.V.), a keyboard, a button panel (30 buttons and indicators), a trackball and a lightpen. A view to the right (Fig. 19) shows a storage scope, three knobs together with their alphanumeric displays, and another button panel.

The button panel is an interesting development of one of our senior technicians. The panel provides 30 push buttons for control purposes, 30 lights for indication purposes (yellow and green states) and an insertable plastic card for both definition and indication of button function. Upon insertion of the card, the computer reads the card number from the holes at the bottom of the card, and refers to a disk file for program numbers associated with each button. Pushing any button then causes the specified program to execute, and this program can have any control function within the capabilities of the control system.

Experimental Areas

Fig. 20 shows the layout of the Experimental Areas. Here you see displayed our hopes for accommodating a large number of experiments in parallel. The positive and negative beams are separated in the switchyard and transported to different areas. The positive beam goes to the main meson area where it traverses two targets, and then on to a target to produce π^- mesons for the biomedical facility, through an isotope production facility and finally into the beam stop which is used as a source of low-energy neutrons and neutrinos. A few percent of each positive beam pulse will be diverted south to provide a high-intensity pulsed neutron source for time-of-flight studies.

The negative beam is diverted to the north and by use of stripping foils, is split into three parts; one to be used in proton -nucleus interaction with the aid of a high-resolution spectrometer, another to produce high energy beams of neutrons in a liquid deuterium target for neutron-nucleus interaction studies, and the third to provide a sliver of beam of exquisitely small angular divergence for small angle scattering experiments.

The three main experimental areas are shown in more detail in Figs. 21-23. The main meson area (Area A) will initially be outfitted with four meson channels designed to provide for both high-precision experiments and a wide variety of meson research studies. The four channels are

a. Low-Energy Pion Channel: Positive and negative pions from 20 to 300 MeV with π^+ flux at 100 MeV of 1.9×10^7 at a resolution $\Delta p/p$ of $\pm$ 0.05 % or 1.5×10^9 at $\Delta p/p$ of $\pm$ 2 %.

b. Energetic Pion Channel and Spectormeters (EPICS): Includes magnetic channel, spectrometers, scattering chamber, and detection system; characterized by good energy resolution (< 50 keV) and good angular resolution (< 10 mrad). The channel will deliver up to 300 MeV with a π^+ flux of 3×10^8/sec at 200 MeV; the spectrometer has maximum momentum of 680 MeV/c.

c. High Energy Pion Channel (P^3): Provides a versatile $\pi^{\pm}$ beam of high energy (100 to 600 MeV) and high intensity ($> 10^{10}$/sec), intended for elementary particle and nuclear reaction experiments.

d. Stopped Muon Channel: Provides $\pm\ \mu$ beams from 0 to 250 MeV/c with intensities $\simeq 10^7$/sec-MeV/c for a variety of muon experiments including polarization studies.

Area B is the nucleon physics area offering beams of protons, either polarized or unpolarized depending on the ion sources in use, and beams of neutrons from a liquid deuterium target, either polarized or unpolarized depending on the angle of scatter. A polarized target is also planned.

Area C houses the High Resolution Spectrometer (HRS), a magnificent instrument capable of providing better than 50 keV resolution in the measurement of the energy lost by a scattered proton from the incident beam. In order to achieve this resolution, the energy spread of the incident beam ($\pm$ 1 MeV) is dispersed in the vertical plane so that protons of different energies strike different portions of the target. The movable portion of the spectrometer is designed to focus scatterd particles of a given energy loss from different portions of the target to a common point on the detector plane high above the target.

Last but not least of the facilities at LAMPF are those intended for practical applications. The practical application which is closest to realization is the use of negative pi mesons in radiotherapy. Figure 24 shows this facility much as it appears today. The building is nearly completed, and the magnets of the pion transport system are being installed.

It has been recognized for many year that negative pi mesons may represent the ultimate radiation source for treatment of deepseated, inoperable, localized malignancies. They offer the opportunity of local, well-controlled depositions of highly ionizing radiations. But up to now the meson beams from all meson-producing accelerators in the world would be inadequate, even if they could be combined, to treat a single patient. LAMPF will produce a suitable dose in about 10 minutes.

Physics with LAMPF

In general, the intense beams of primary protons and secondary neutrons, π mesons, muons, neutrinos, and γ rays will open the way to new information about the structure of the atomic nucleus and about the basic forces which govern that structure.

New approaches will also be opened in chemistry because of the capability to produce nuclear species, both neutron-rich and proton -rich, which are not now available for study. In addition, the availability of large numbers of muonic atoms will permit the development of new kinds of atomic physics and chemistry research through the replacement of electrons by μ^- and or protons by μ^+ in atoms and molecules.

The physics program for LAMPF can be outlined as follows:

I. Nuclear Forces

A. Nucleon-nucleon interaction. In particular, there is a requirement for better and more systematic information about the interaction between one nucleon and another. Required are the difficult double- and triple-scattering experiments, the polarization, depolarization, rotation, and spin-correlation experiments.

These experiments should, at the very least, lead to a systematic description of the nucleon-nucleon interaction in terms of a potential whose parameters vary smoothly with energy.

B. Pion-nucleon interaction. All the experiments discussed for the nucleon-nucleon system have their analogies with incident π's. Pion-nucleon interactions are interesting in their own right and also because the exchange of pions between nucleons is thought to be a fundamental process in nuclear structure. Higher intensities are needed to determine precise values for polarization of the recoil nucleon and of the triple-scattering parameters. The latter are, in principle, redundant, but they are much more sensitive to the higher phase shifts than single- and double-scattering experiments. Even the pion production process in nucleon-nucleon collisions has not been studied in sufficient detail.

C. Pion-pion interaction. The pion-pion interaction has been identified as perhaps the most important one in high-energy physics. It can be studied by means of the (π, 2π) reaction on nucleons. The physical picture is that the incident pion strikes a virtual pion in the meson cloud around the target nucleon, leaving the nucleon relatively undisturbed. Therefore, one is observing something like quasi-elastic pion-pion scattering.

II. Nuclear Structure

A. Nucleons as probes. 500-800 MeV nucleons are particularily well suited for probes of nuclear structure. The mean-free path of such nucleons in nuclear matter are relatively large; the probability of multiple scattering is minimal; the DeBroglie wavelength is smaller than internucleonic distances; and the impulse approximation can be used with reasonable confidence. It has already been possible to study the single particle states in nuclei by means of (p, 2p) reactions, which provide information of the angular momentum, parity, binding energy, and the momentum distribution of individual nucleons. Similar information can be obtained with pickup relations. Future progress requires higher intensity and extension to (p, np) reactions.

High intensity beams of nucleons will make possible very precise polarization as well as differential and total cross-section measurements. It should then be feasible to determine whether an optical model description of nucleon-nucleus interactions, with parameters which vary smoothly with energy, is as useful above 100 MeV as it is at lower energies. At what point does a nucleon cease to see mainly the effects of the nucleus as a whole ? It is at present not clear at what energy the phenomenological description, which appears useful at low energies to very large scattering angles, will break down at high energies and high momentum transfers.

B. Pions as probes. Like the nucleon, the pion is a strong-interaction probe, but it is different and therefore provides a new set of windows through which to view nuclear processes. It is different in that it has different mass, different spin, different isotopic spin, and liberates a great deal of energy on capture. For all these reasons the pion is sensitive to different aspects of the nucleus than are nucleons.

Fast pions will be useful for elastic and inelastic scattering experiments. In the former it will be interesting to see whether an optical model can descirbe the pion-nucleus interaction and whether the parameters are derivable from pion-nucleon scattering. Experiments on (π, π'X) reactions should permit studies of shell-model states and clusters.

In the absorption process, one introduces 140 MeV of energy without angular momentum. This will permit study of statistical processes in nuclei without the complication of angular-momentum dependent processes.

Pi-nucleus inelastic scattering should produce preferentially highly excited nuclear states with small angular momentum.

C. Muons as probes. Twenty years ago, J.A. Wheeler wrote a paper entitled "Mu Meson as a Nuclear Probe Particle". Fast muons, like electrons, can be used to study the electromagnetic form factor of the nucleus and its excited states. The muon, like the electron, avoids the complication of strong interaction between the probe and the target nucleons. Its advantage over the electron is that, because of its higher mass, it produces far less bremsstrahlung, it is polarized, and it liberates a great deal of energy on capture. For example, although the cross section is low, one can observe, with meson factory intensities, the reaction $\mu^- + d \rightarrow n + n + \nu_\mu$. Measurement of the energy and angular distributions of the two neutrons can shed light on the neutron-neutron scattering length. Of the muon experiments proposed to date, one rather simple but unusual experiment involves the reaction $\mu^- + {}^6Li \rightarrow T + T + \nu_\mu$. Here we have an opportunity to substantially improve the accuracy to which the mass of the mu-neutrino is known.

III. Mu-mesic X-rays.

When captured by a heavy nucleus, a negative muon forms an atom of nuclear dimensions. As the muon falls from one Bohr orbit to the next, X-rays are emitted. A muon in the lowest atomic orbit of a heavy atom spends approximately half its time inside the nucleus; and during its lifetime traverses ~5 meters of nuclear matter. The nuclear electric field must, therefore, have a profound influence on the atomic energy levels and, conversely, the properties of this field are determinable from a knowledge of the muonic levels. In lead, for example, the first muonic Bohr orbit has a radius of 3×10^{-13} cm, whereas the radius of the lead nucleus is 7×10^{-13} cm.

Even the heaviest muonic atoms have a simple spectroscopy, like that of the H atom. There is no electron screening effect because all muonic Bohr orbits below $n \cong 14$ are within the K electron orbital.

The muonic X-ray studies made thus far are only a beginning. The availability of 10^4 higher muon fluxes will permit not only better statistics but also thinner targets and better resolution of the X-ray lines.

IV. Weak Interaction.

One of the most important experiments in the theory of weak interactions is neutrino-electron scattering. Here is the possibility to look at weak interactions in their purest form. Even a crude measurement of the cross section for this process will have an important bearing on the theory. These experiments require the maximum fluxes obtainable from meson factories.

The conservation laws for leptons state that in all reactions the algebraic sum of electron leptonic numbers, and also of muon leptonic numbers, must not change. That is, electron and muon quantum numbers are separately conserved. Presently available data are consistent with four different lepton conservation laws. The LAMPF neutrino source is ideally suited to distinguish between these four prossibilities.

Current Status of Operation

The machine has operated only once at full energy, and at that time, only for low peak and average currents. Since then, it has operated numerous times at energies of 400 to 500 MeV, and many times at energies of 211 MeV and below. Most of the beam time to date has been devoted to systems checkout and development, stability and reproducibility studies, accelerator and beam measurements, and development of tuning procedures.

A low-duty beam stop and shield wall at 211 MeV makes operation at that energy possible in parallel with installation and maintenance in the switchyard and experimental area. Since much access was needed to these areas during the past year, and most beam related system checkouts could be accomplished with beams of that energy or less, much of the operation during the past year has been with the 211 MeV target inserted.

Transmission through the machine (after the initial capture) as measured by current transformers is often about 99 %. Neverthless, the loss of 1 % of the beam is still too high by a factor of 10-100 for continuous operation at full duty. Further progress on reducing these losses must await modification of the beam spill radiation detectors, redesign of the beam position monitors, realignment of some of the quadrupole doublets, and reconnections of some of the steering magnets. Majority of this rework should be done by July.

The energy spectrum of the beam has been measured a several energies between 200 and 400 MeV, yielding a FWHM value of ~0.25 % $\Delta p/p$. This value is comfortably within the predicted value.

The emittance of the 211 MeV beam has been measured at the end of the accelerator and yields values of about $\pi/10$ cm-mrad. This value is close to the predicted value, and well within the π cm-mrad acceptance of the early portion of the switchyard and experimental area transport systems.

Simultaneous acceleration of H^+ and H^- beams to about 300 MeV was demonstrated in May. Although some of the steering and tuning problems were anticipated, an unexpected steering problem was discovered. Analytical and computer analysis suggests the solution to lie in a reconnection of some of the steering magnets. This work is in progress.

The beam line to Area B was completed during June of this year, and in July, 250 MeV beam was transported to the permanent beam stop. In August, the beam line to Area A was completed, 447 MeV beam was transported through the area into a temporary beam stop, and the first pi-mesons were identified through the Low-Energy Pion Channel.

Evidence to date indicates that the design and construction of the facility is sound, and that the tuning problem, while difficult, is tractable. Thus we anticipate that the accelerator will provide the requisite beams in a very satisfactory manner.

Figure Captions

1. Aerial view of LAMPF
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3. Scientific purposes of LAMPF
4. Aerial view of LAMPF
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21. Experimental Area A
22. Experimental Area B
23. Experimental Area C
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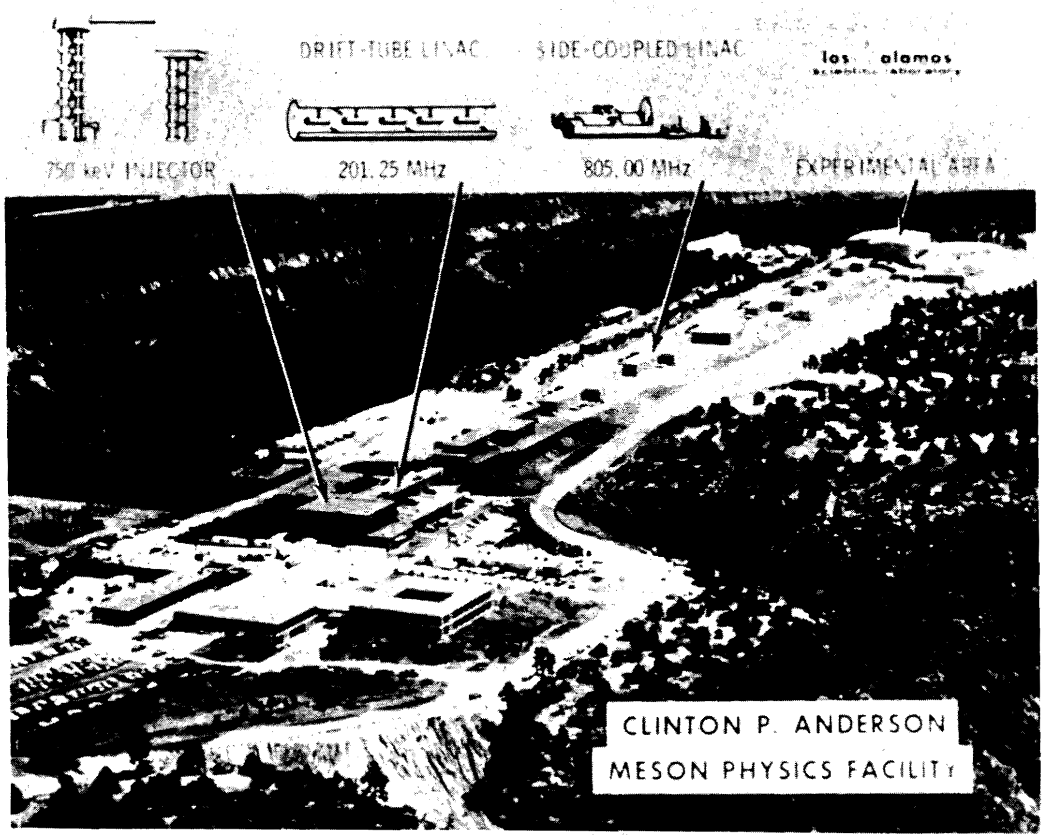


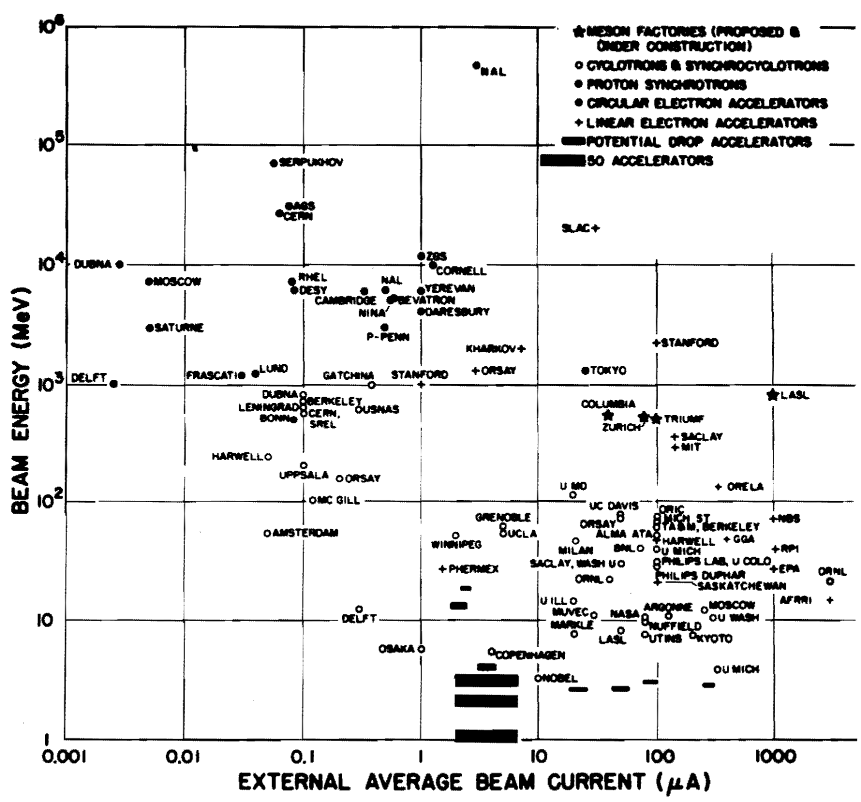
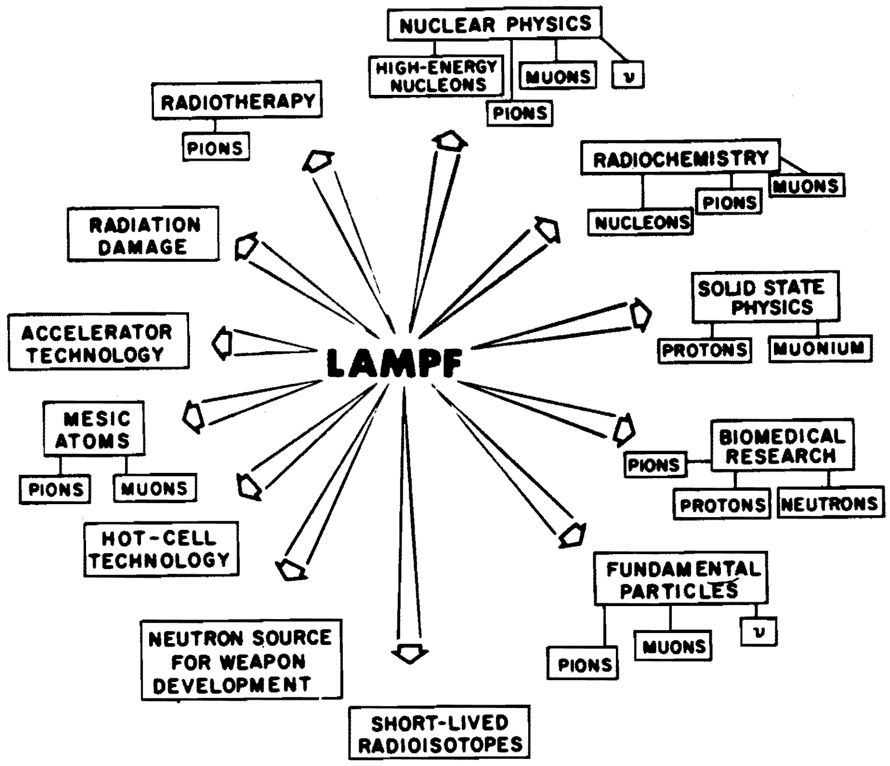
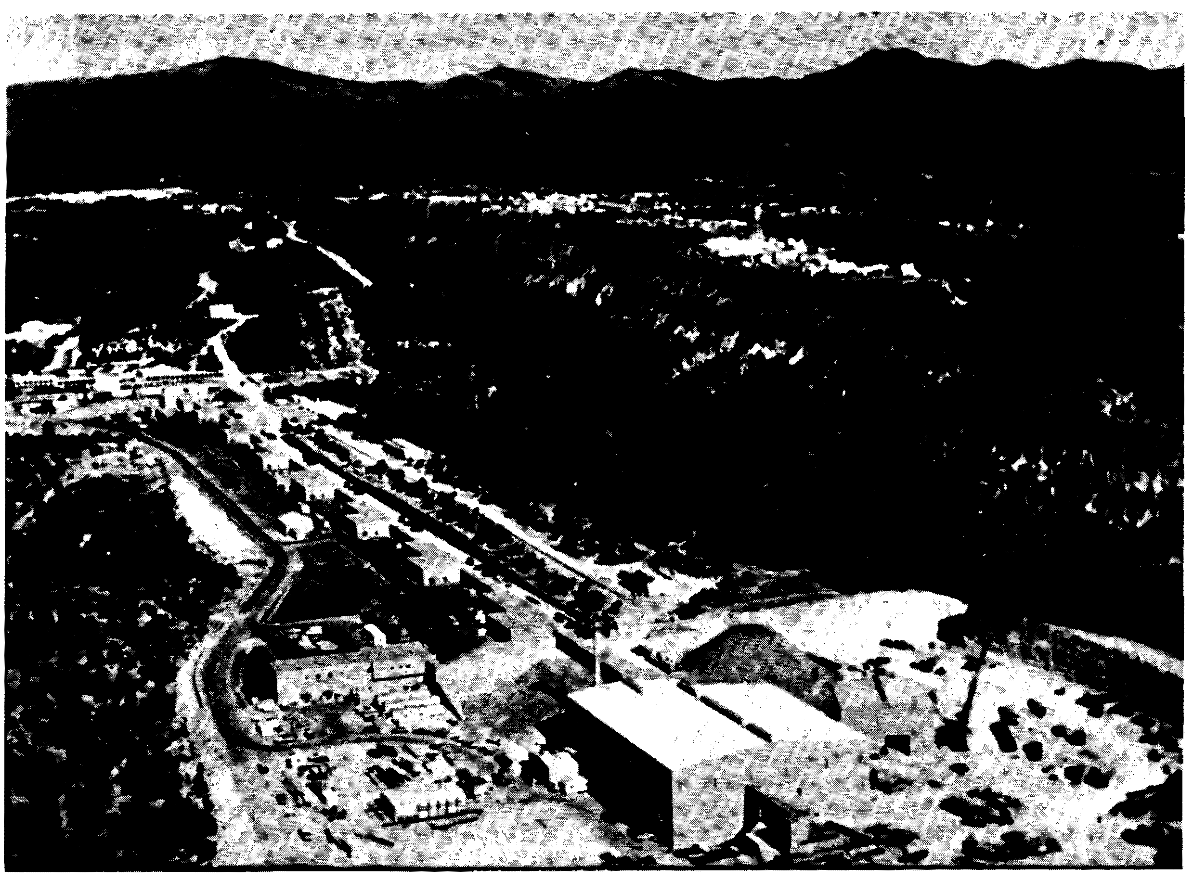
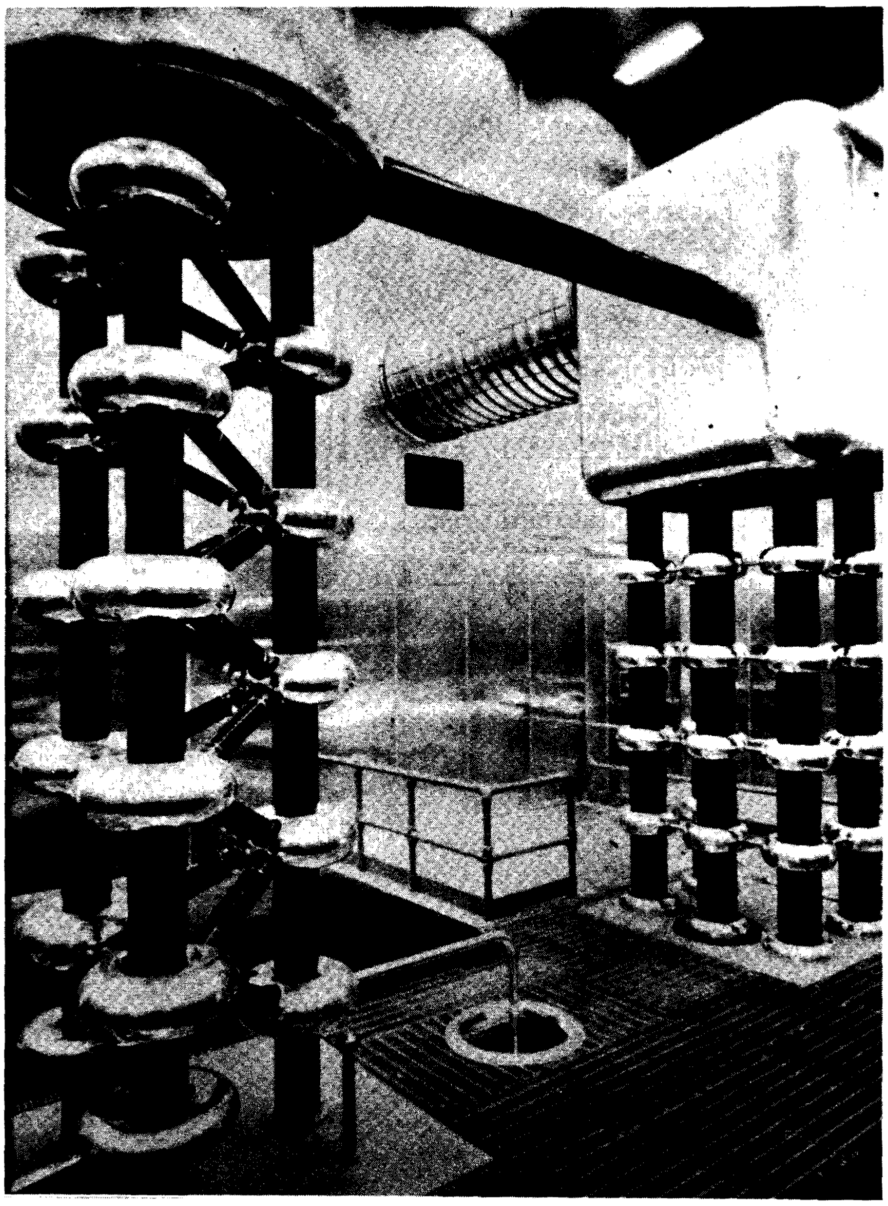
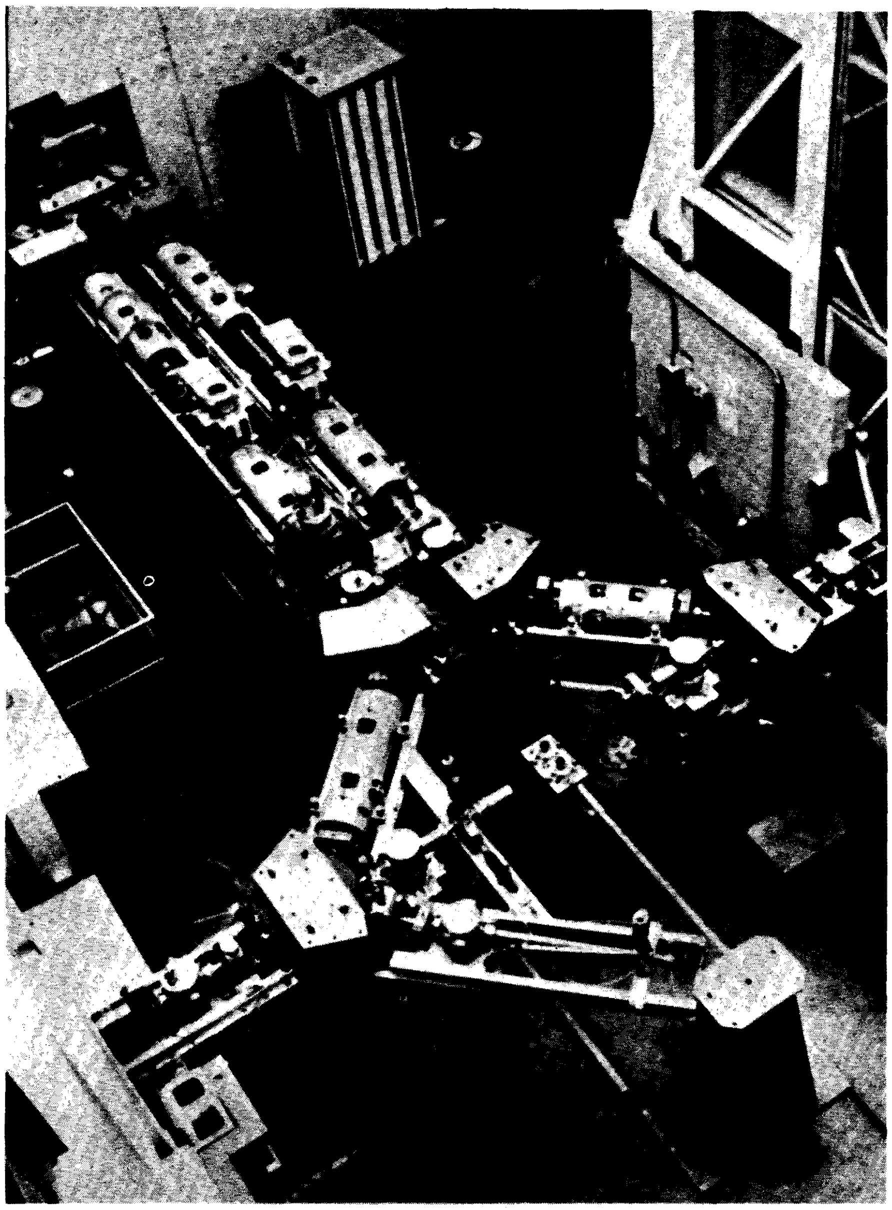


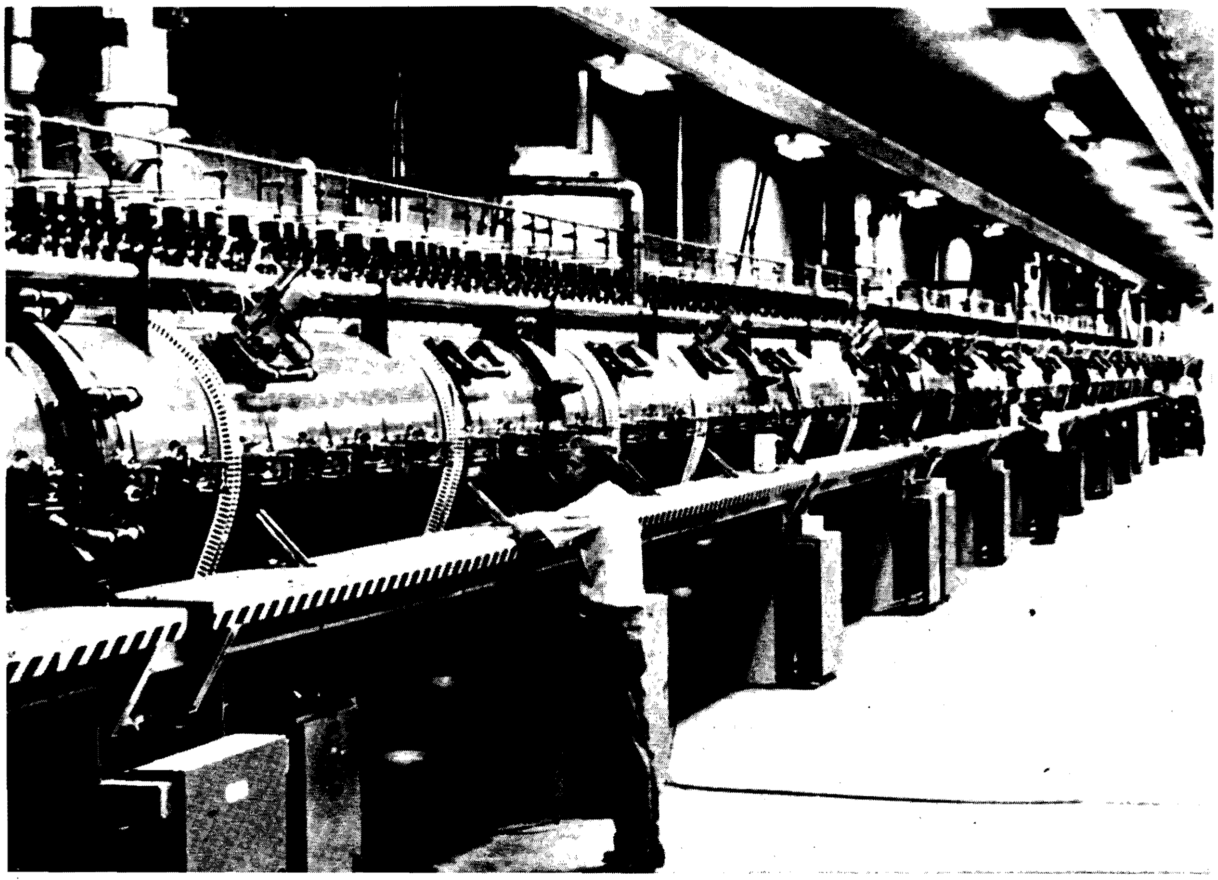
Figure I World-wide Inventory of Research Accelerators

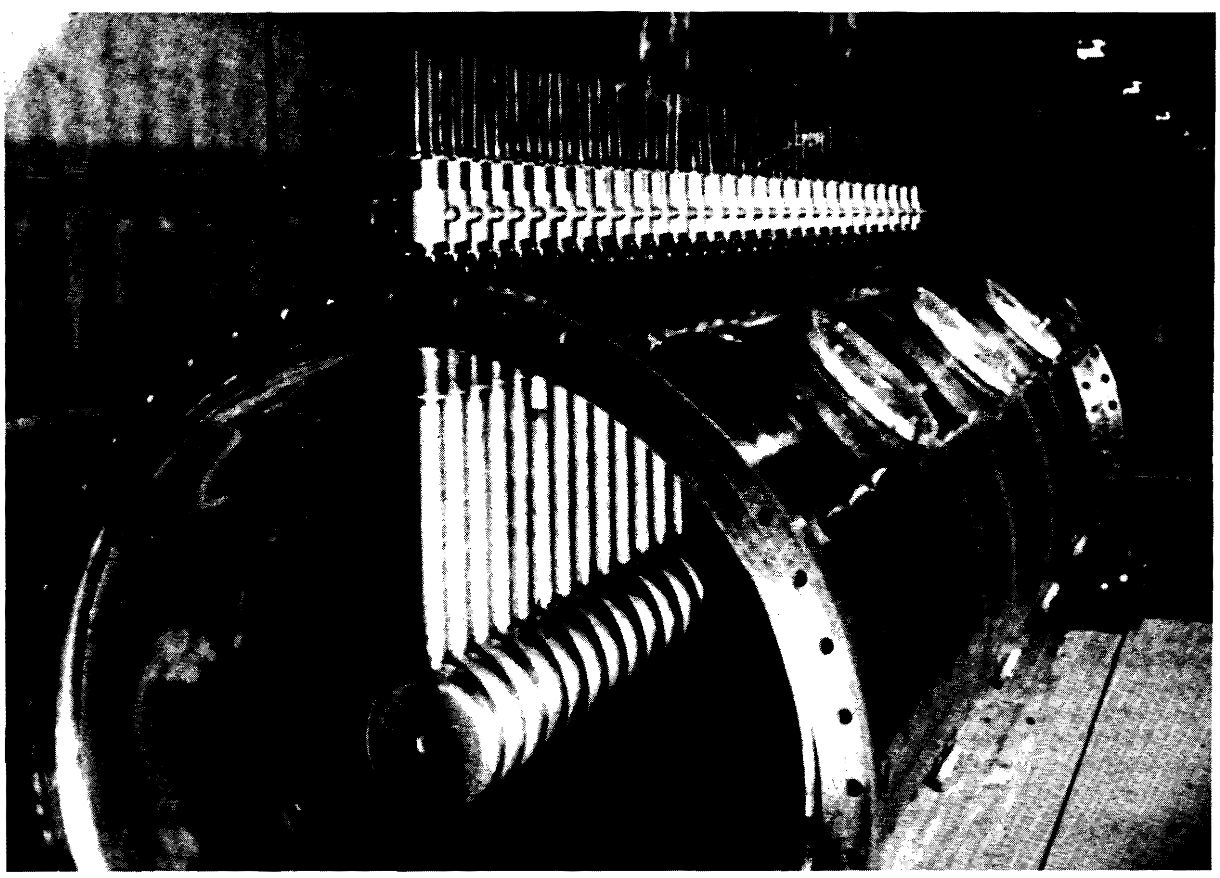

LAMPF
NUCLEAR PHYSICS
HIGH-ENERGY NUCLEONS
MUONS
ν
PIONS
RADIOTHERAPY
PIONS
RADIOCHEMISTRY
MUONS
PIONS
NUCLEONS
RADIATION DAMAGE
SOLID STATE PHYSICS
PROTONS
MUONIUM
ACCELERATOR TECHNOLOGY
MESIC ATOMS
PIONS
MUONS
BIOMEDICAL RESEARCH
PIONS
PROTONS
NEUTRONS
HOT-CELL TECHNOLOGY
FUNDAMENTAL PARTICLES
PIONS
MUONS
ν
NEUTRON SOURCE FOR WEAPON DEVELOPMENT
SHORT-LIVED RADIOISOTOPES

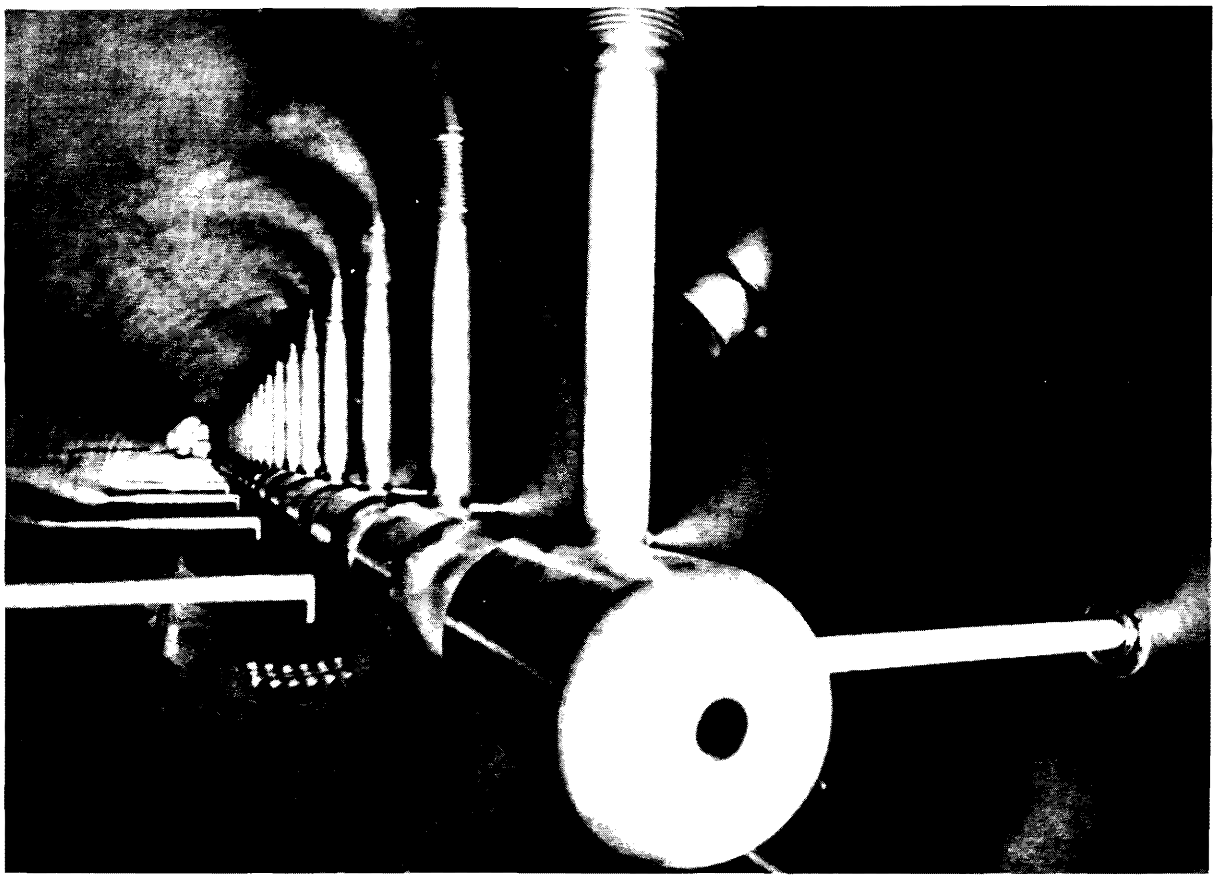


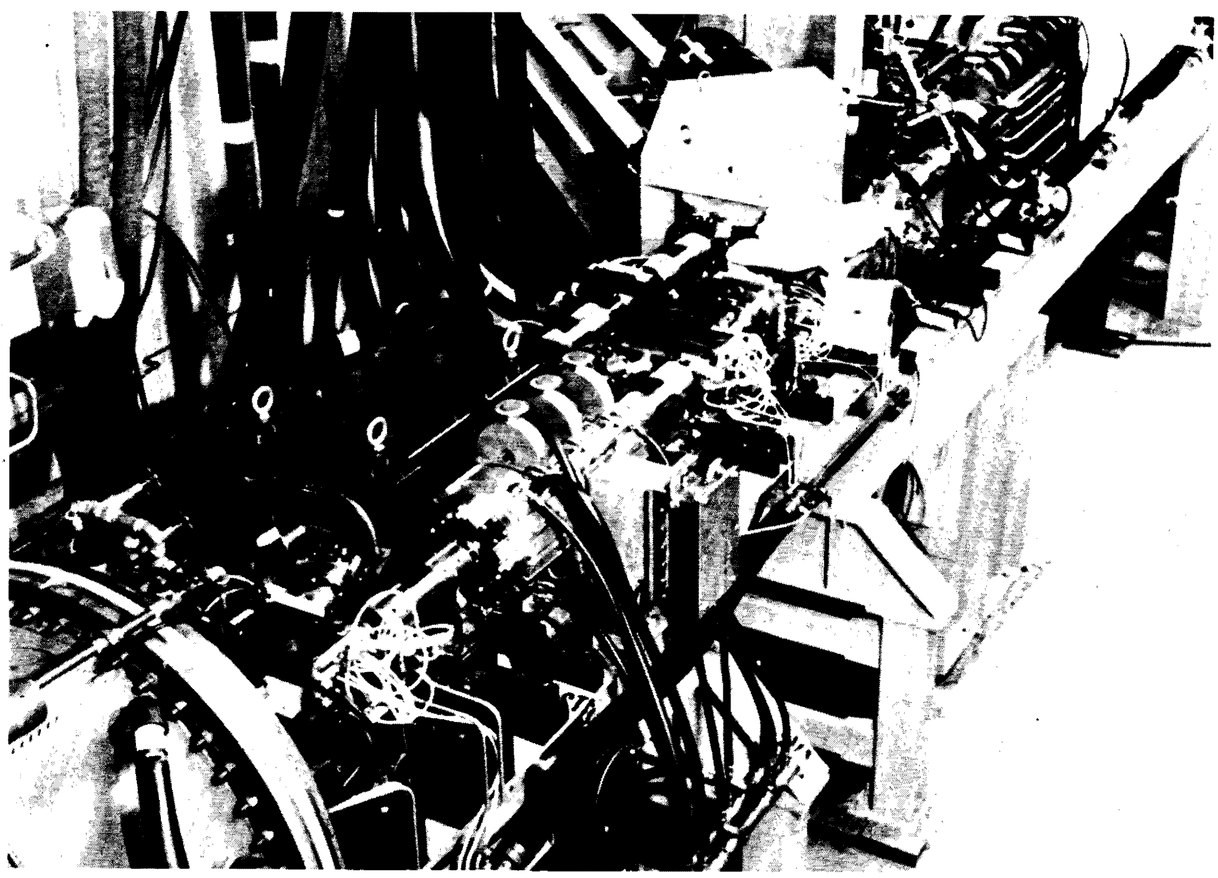


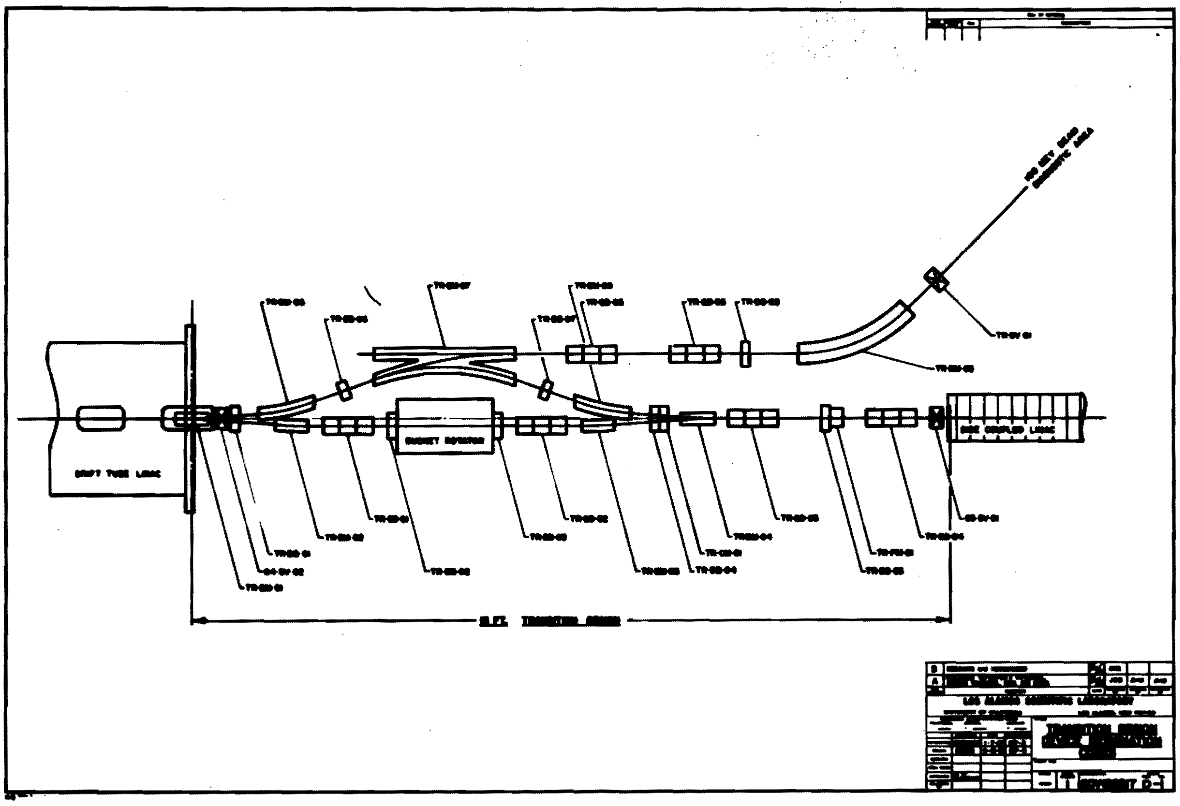


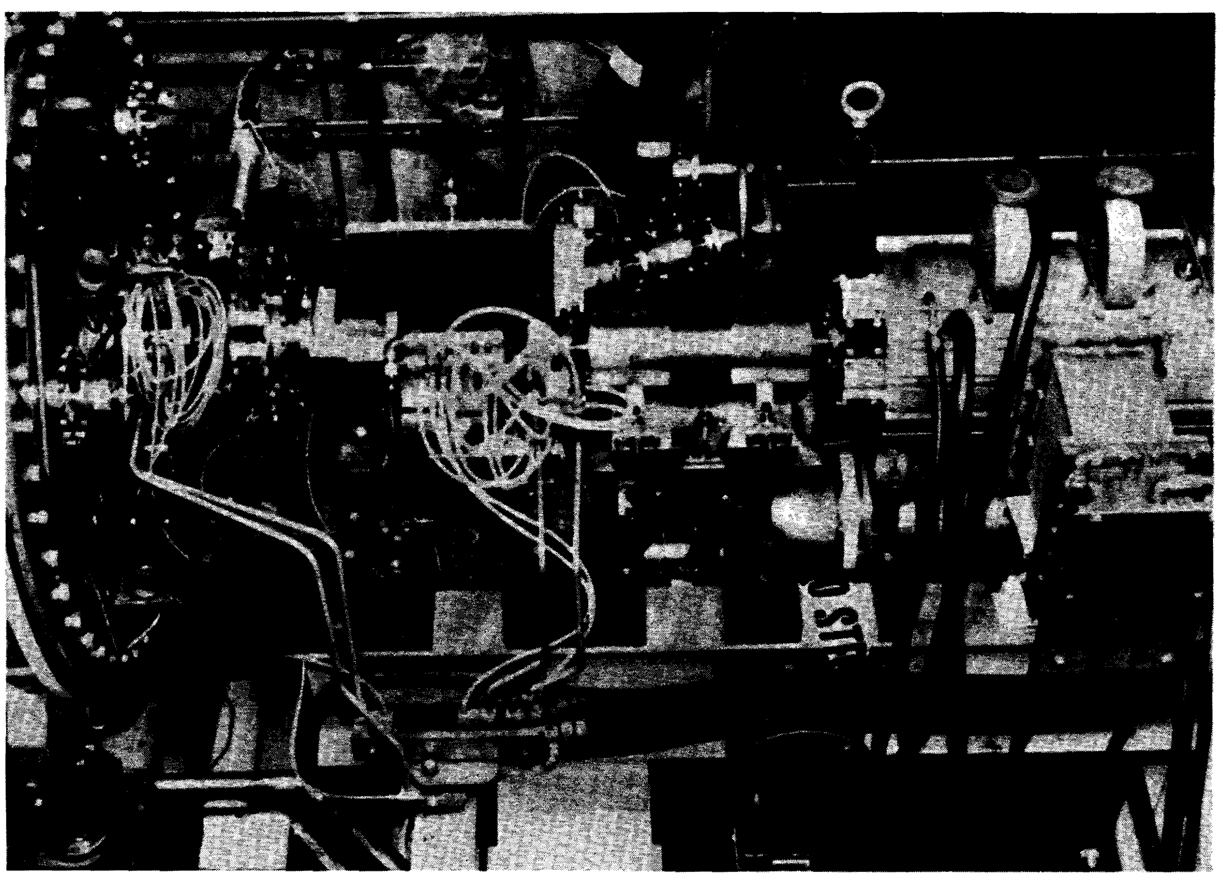


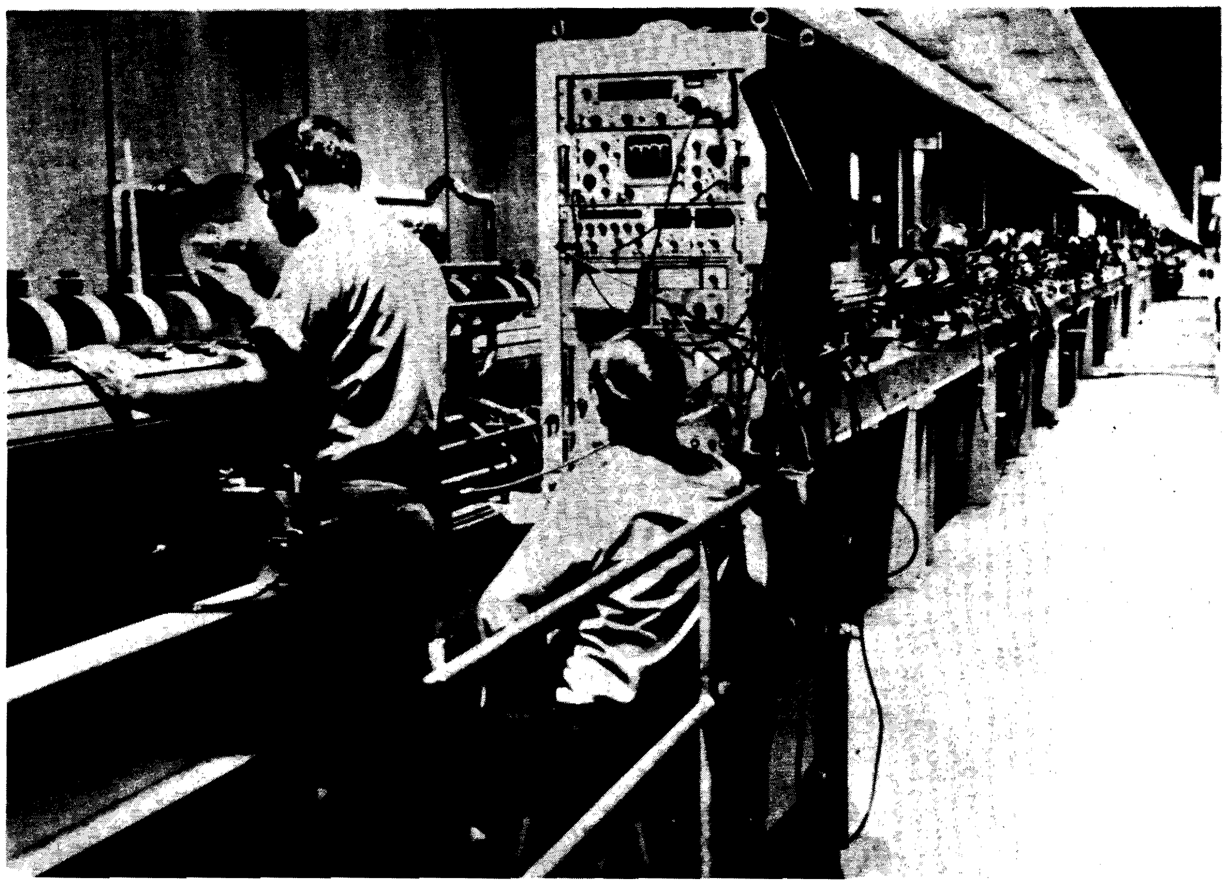


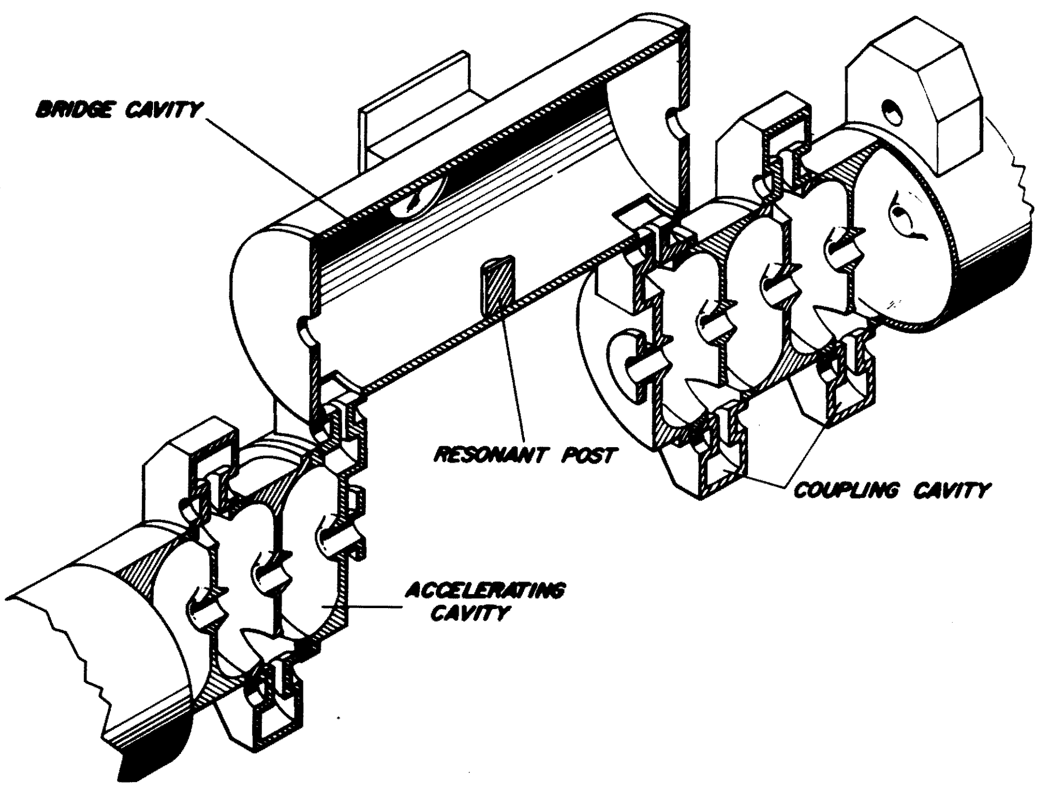


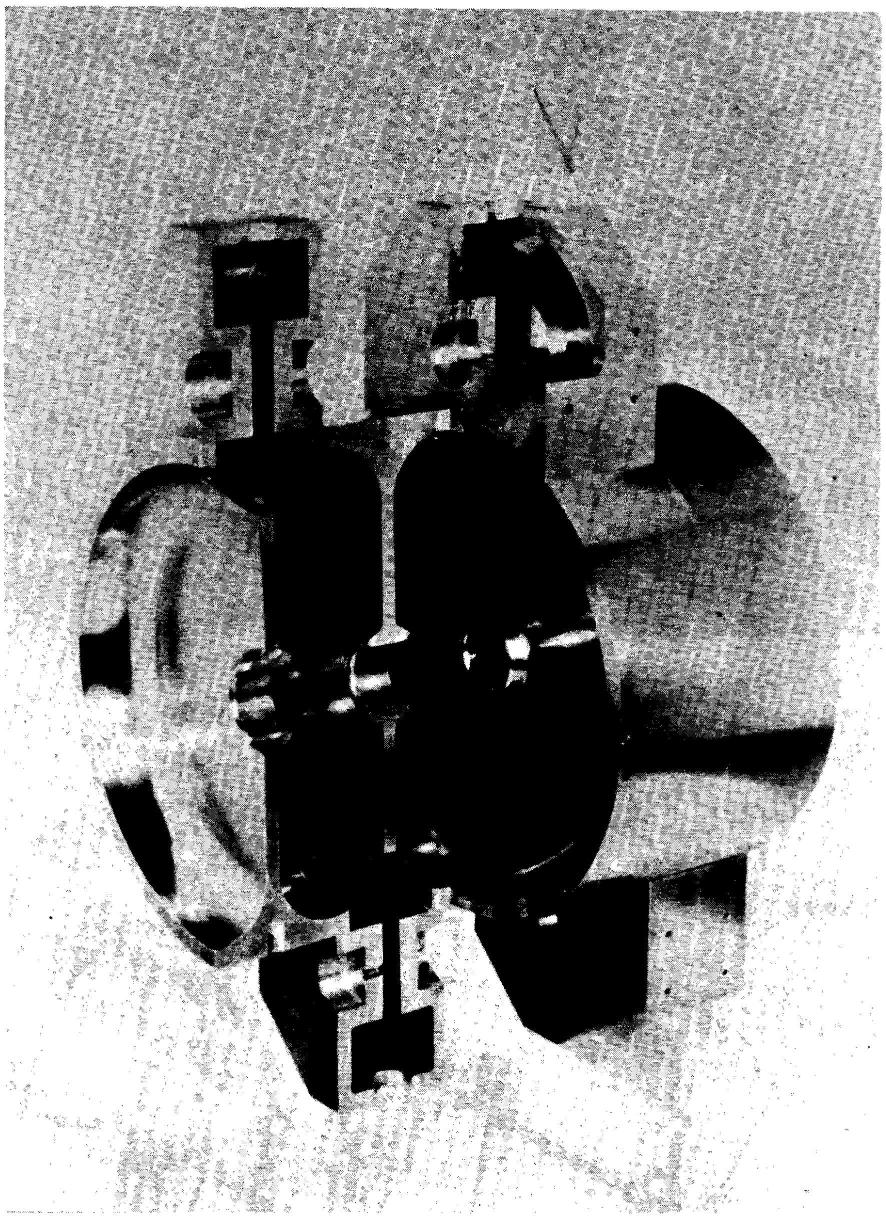


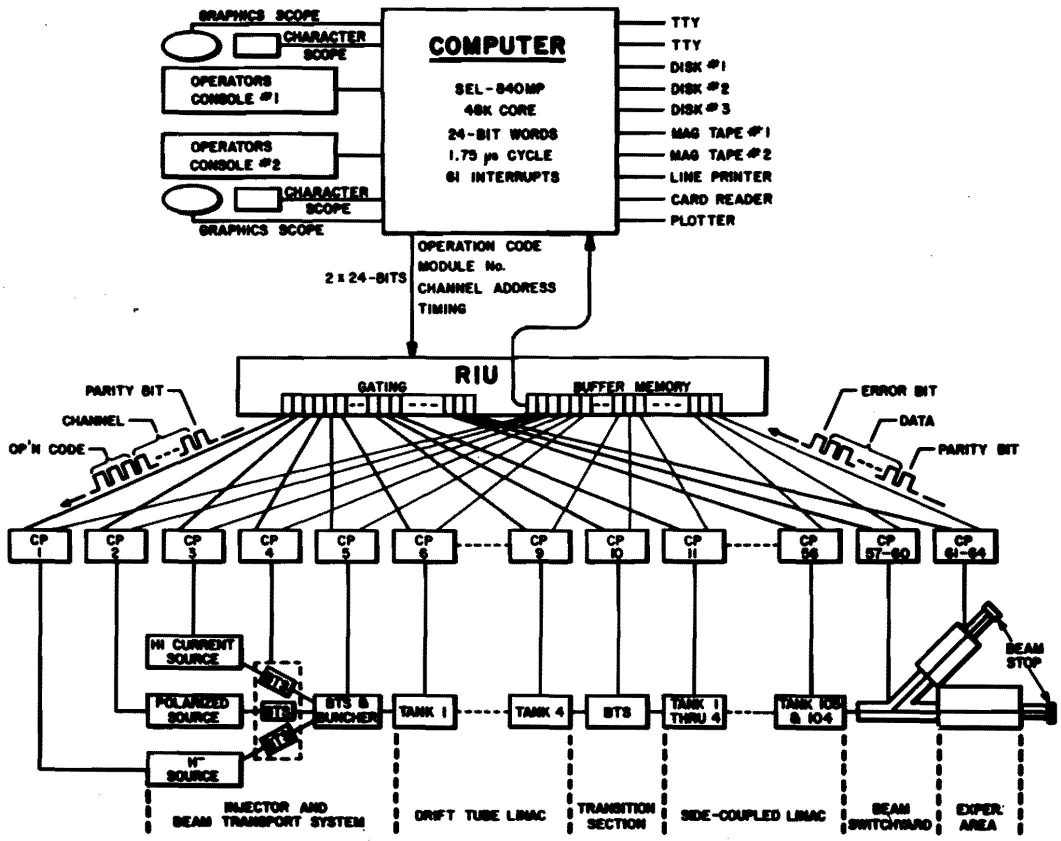

DRIFT TUBE LINAC
SIDE COUPLED LINAC

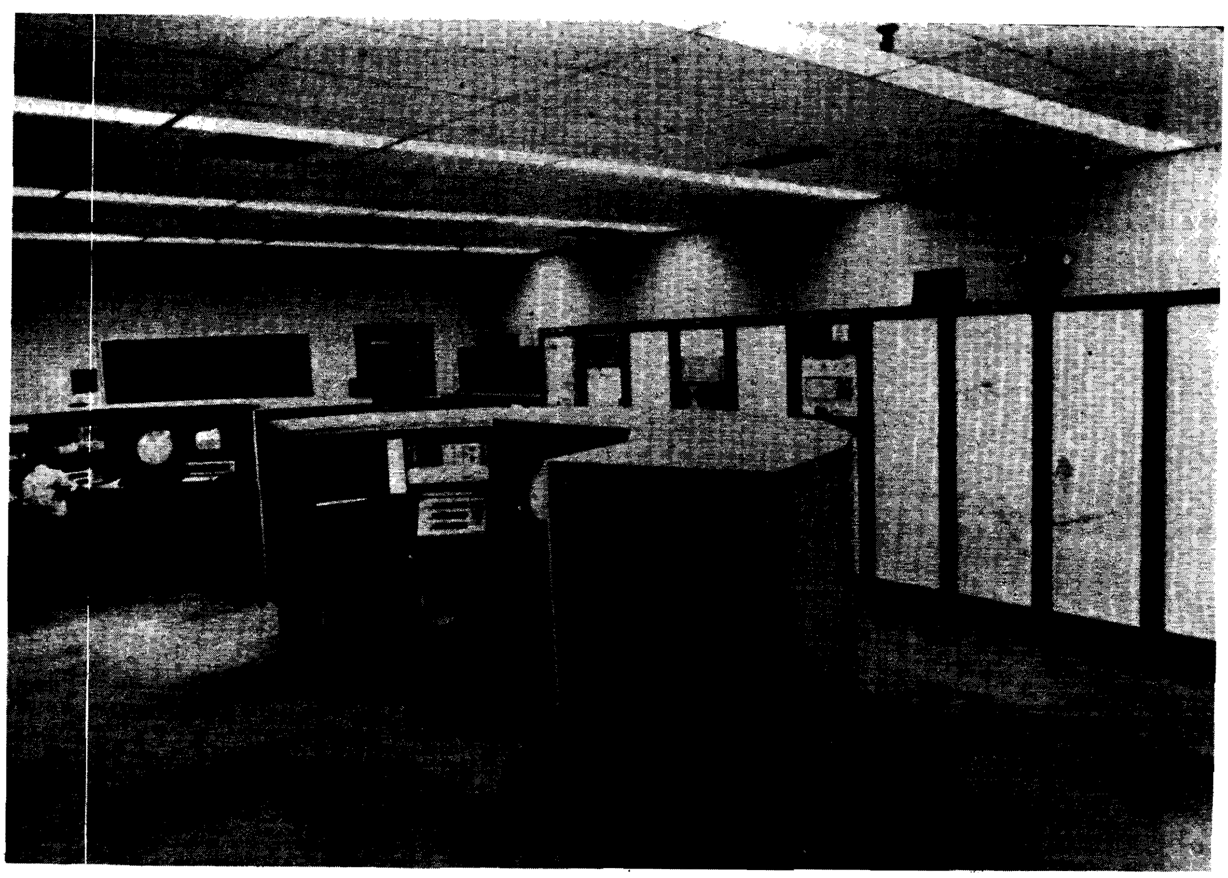


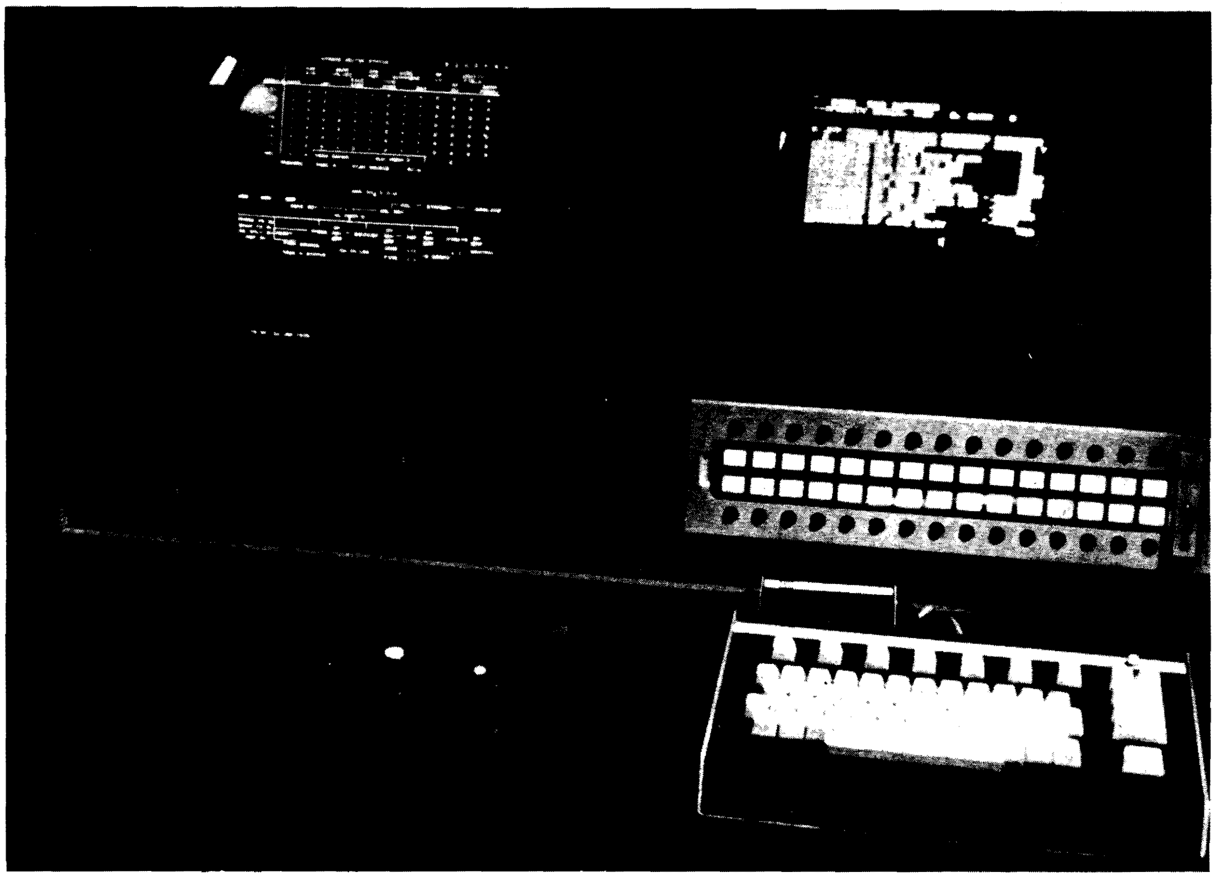


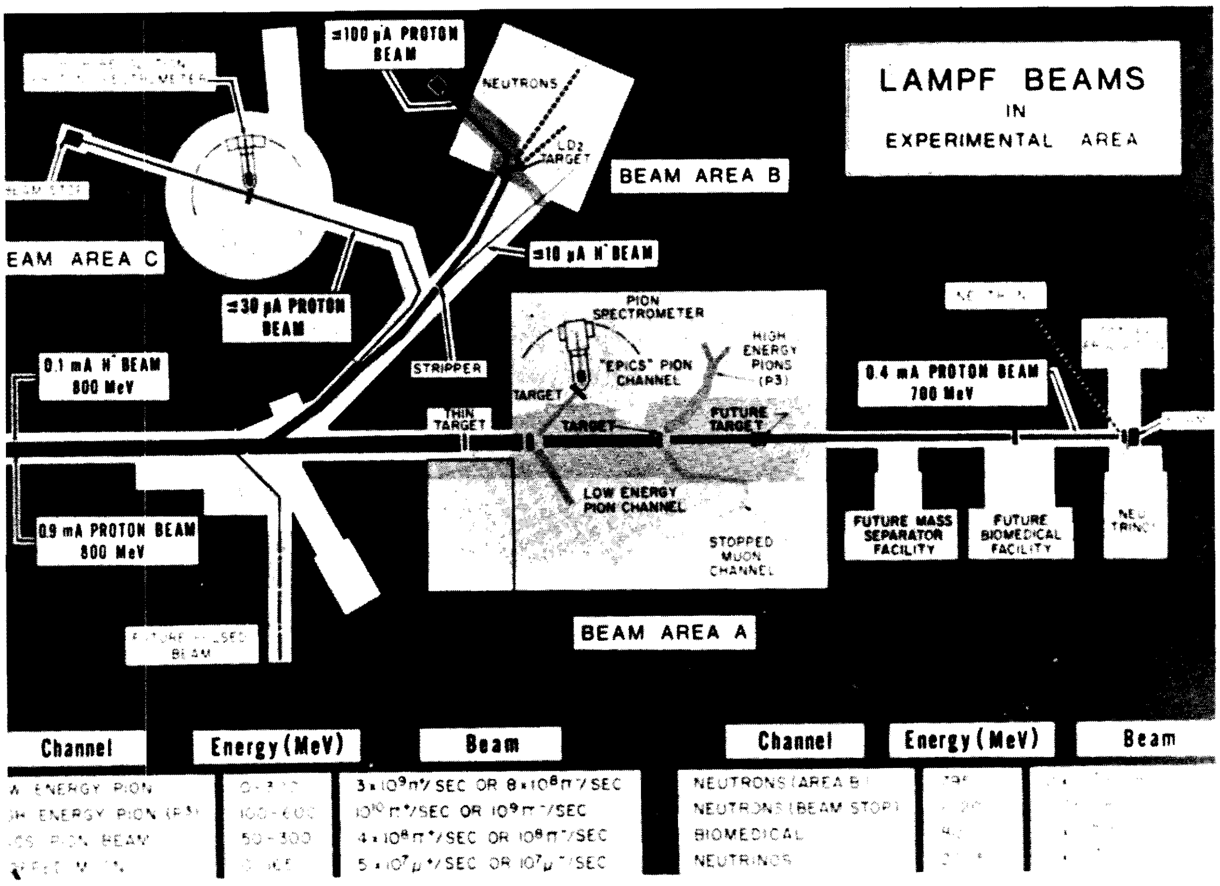

BRIDGE CAVITY
RESONANT POST
COUPLING CAVITY
ACCELERATING
CAVITY



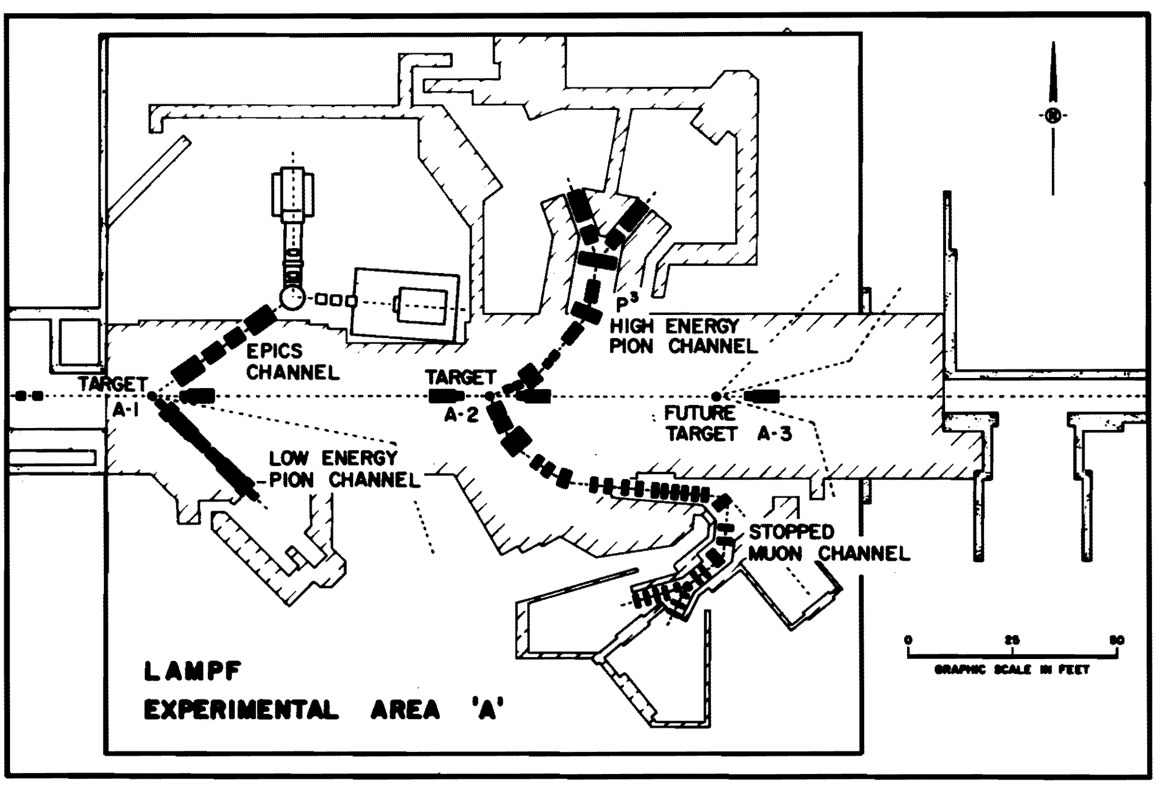

GRAPHICS SCOPE
CHARACTER SCOPE
OPERATORS CONSOLE #1
OPERATORS CONSOLE #2
CHARACTER SCOPE
GRAPHICS SCOPE
COMPUTER
SEL-840MP
48K CORE
24-BIT WORDS
1.75 μs CYCLE
61 INTERRUPTS
TTY
TTY
DISK #1
DISK #2
DISK #3
MAG TAPE #1
MAG TAPE #2
LINE PRINTER
CARD READER
PLOTTER
2 x 24-BITS
OPERATION CODE
MODULE No.
CHANNEL ADDRESS
TIMING
RIU
GATING
BUFFER MEMORY
PARITY BIT
CHANNEL
OP'N CODE
ERROR BIT
DATA
PARITY BIT
CP 1
CP 2
CP 3
CP 4
CP 5
CP 6
CP 9
CP 10
CP 11
CP 56
CP 57-60
CP 61-64
H CURRENT SOURCE
POLARIZED SOURCE
H⁻ SOURCE
BTS
BTS & BUNCHER
TANK 1
TANK 4
BTS
TANK 1 THRU 4
TANK 101 & 104
BEAM STOP
INJECTOR AND BEAM TRANSPORT SYSTEM
DRIFT TUBE LINAC
TRANSITION SECTION
SIDE-COUPLED LINAC
BEAM SWITCHYARD
EXPER. AREA



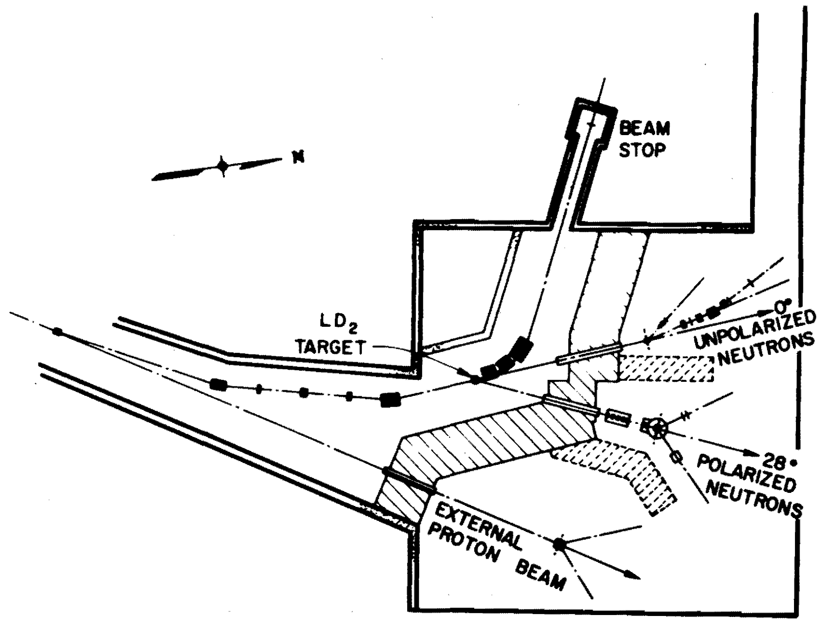




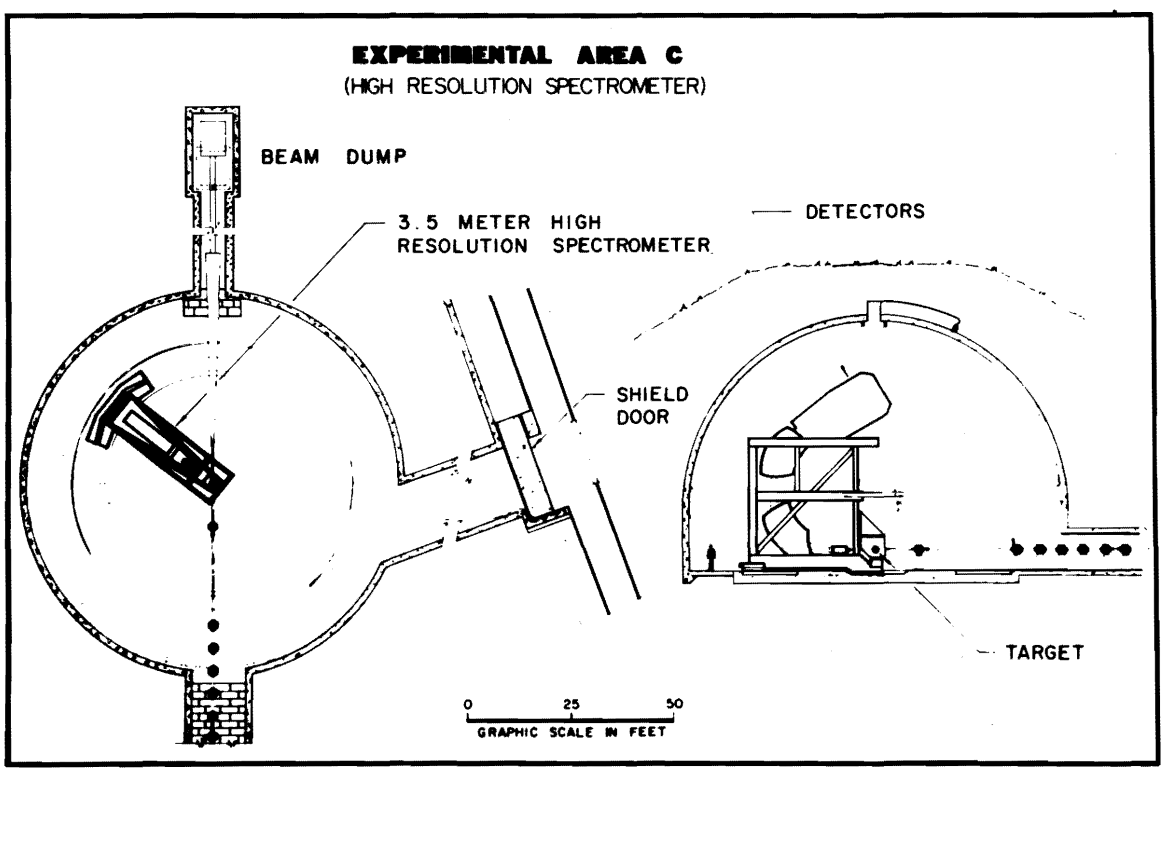
LAMPF BEAMS
IN
EXPERIMENTAL AREA
≤100 μA PROTON BEAM
NEUTRONS
LD2 TARGET
BEAM AREA B
EAM AREA C
≤10 μA H⁻ BEAM
≤30 μA PROTON BEAM
STRIPPER
0.1 mA H⁻ BEAM
800 MeV
PION SPECTROMETER
HIGH ENERGY PIONS (P3)
"EPICS" PION CHANNEL
TARGET
THIN TARGET
FUTURE TARGET
0.4 mA PROTON BEAM
780 MeV
LOW ENERGY PION CHANNEL
STOPPED MUON CHANNEL
0.9 mA PROTON BEAM
800 MeV
FUTURE MASS SEPARATOR FACILITY
FUTURE BIOMEDICAL FACILITY
BEAM AREA A
Channel
Energy (MeV)
Beam
3×10⁹π⁺/SEC OR 8×10⁸π⁻/SEC
10¹⁰π⁺/SEC OR 10⁹π⁻/SEC
50-300
4×10⁸π⁺/SEC OR 10⁸π⁻/SEC
5×10⁷μ⁺/SEC OR 10⁷μ⁻/SEC
NEUTRONS (BEAM STOP)
BIOMEDICAL
NEUTRINOS

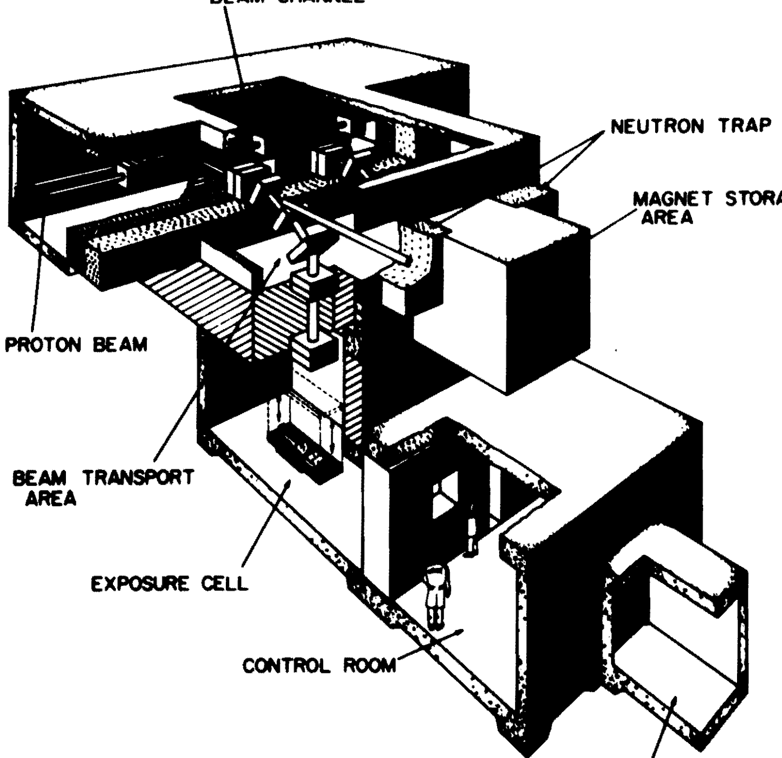


EPICS CHANNEL
P³
HIGH ENERGY PION CHANNEL
TARGET A-1
TARGET A-2
FUTURE TARGET A-3
LOW ENERGY PION CHANNEL
STOPPED MUON CHANNEL
LAMPF
EXPERIMENTAL AREA 'A'
GRAPHIC SCALE IN FEET



BEAM AREA 'B'
NUCLEON PHYSICS LAB.





PROPOSED RADIATION THERAPY FACILITY