STATUS AND PERFORMANCE OF LAMPF*

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I. INTRODUCTION

It is a pleasure to report to you on the status of LAMPF. The whole linac fraternity, as represented by you here today, should take pride in LAMPF because it embodies contributions from all the centers of linac science. Concerning Los Alamos, it has a long history of accelerator development and interest in fundamental nuclear physics. The history and prehistory of LAMPF has been set down by Livingston in his clear and thorough manner.[1] From 1954 to 1957, Ribe, McGuire, Argo, myself, and others designed a K-meson and hyperon factory, based on a 2-GeV spiral ridge cyclotron. The idea for a pi meson factory at Los Alamos is contained in a memo from Louis Rosen to Jerry Kellogg, May 16, 1962. That summer Don Hagerman, Ed Knapp, and I became interested in the idea, and with the help of many other LASL staff members, a preliminary proposal for a meson factory was written in December 1962, based on a 750-MeV proton linac. That linac proposal in turn drew heavily on earlier studies by a group at Yale led by Vernon Hughes, and on even earlier work by the British group at Harwell. In February 1963, Group P-11 was formed to design the accelerator. It included Hagerman, Knapp, McGuire, and myself, and later that spring a graduate student, Bob Jameson, joined us. Dick Taschek and Louis Rosen were the P-Division Leaders then. A much more definitive proposal for an 800-MeV, 1-mA proton linac was made in September 1964, based on two additional years of design studies and outlining the research programs in medium-energy physics. The present machine design is close to that set forth in the 1964 proposal -- the so-called "Blue Book." A new Division of Medium-Energy Physics (MP Division) was formed in July 1965 with Rosen as Division Leader and myself and Fred Tesche as Associate Division Leaders. A primary purpose was to continue with the design and development of the meson facility.

The total budget estimate for LAMPF was $55 million. Preliminary research and architect-engineering funds totaling $4.7 million were allocated during FY-66 and 67 for design and site development. In the FY-68 budget, construction funds of $3.7 million were authorized by the Congress and the President, so that physical construction began with a groundbreaking ceremony for the Equipment Test Laboratory on February 15, 1968. A little more than four years later we saw the first 800-MeV beam on June 8, 1972, somewhat ahead of our target date of July 1, 1972. Figure 1 shows the site before construction started and some of the remains of the previous occupancy. Figure 2 shows the site as it now looks for the administrator and theorist; Fig. 3, a view for the experimental user: the HRS, the meson area, and the biomedical area; Fig. 4, the waveguide linac for the accelerator person; Fig. 5, a knock-on delta ray spectrum demonstrating the first 800-MeV operation; Fig. 6, beam current and beam loading along the linac for first 800-MeV turn-on.

A construction steering committee headed by Don Hagerman guided the installation, final tuning, checkout, and initial operation of the linac.

We are proud of the fact that the final budget figure of $57 million is rather close to the FY-1967 budget estimate, despite a large increase in the experimental facilities. Although much remains to be done, preliminary data on the performance of the

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linac indicate that it will be a very successful accelerator.

Since the enthusiasm and vision of Senator Clinton P. Anderson have been so vital in making this project a reality, it was dedicated last month as the Clinton P. Anderson Meson Physics Facility of the Los Alamos Scientific Laboratory.

Beam loss in the linac and in the transport areas, and consequent activation of components, could very well be a determining factor in what level of intensity is feasible. The initial operating experience is very good with respect to beam loss. Remembering our design goal for full operation is 1 mA, it remains to be seen what problems, connected with beam loss at the 10^{-3} level of peak beam, may still arise in the waveguide linac and in the switchyard.

The first nuclear chemistry discovery at LAMPF was made a few weeks ago; namely, a new neutron-rich isotope of thorium has been produced. Carl Orth, Bill Daniels and Bruce Dropesky (of CNC-11) have succeeded in producing and identifying the isotope ^{236}Th, now the heaviest isotope of thorium known. On September 25, a 1-mil foil of depleted ^{238}U was irradiated with about 3 μA of 100-MeV protons in the "north port" targeting station for 20 min. After extensive fast chemistry at TA-48 to separate and purify the thorium fraction, particularly from the large amount of fission products, Ge(Li) spectroscopy on the final sample clearly showed the known γ-spectrum of 9-min ^{236}Pa daughter growing and then decaying with about a 40-min half-life, that of the ^{236}Th parent. The ^{236}Th appears to decay predominantly by a direct beta transition to ^{236}Pa.

We are presently in the stage of completing engineering, fabrication, and installation of all the complex systems comprising the experimental facilities. Time, money, and manpower all impose serious restrictions in this area. It is our goal to operate the secondary beam lines in the spring of 1973 at the reduced current of 1 μA, which will enable several experiments to begin on the meson beam lines and several on the nuclear beam lines. Higher-current operation will become possible as the experimental areas are further developed in 1973. Below we give some current details of the performance of the linac systems and of the plans and construction activities for experimental facilities.

Injectors

Injection into the linac is at 750-keV dc, the voltage originating with a Cockcroft-Walton set. The ion source is a duoplasmatron with a cup designed to give a flat plasma surface.[2] The ion source is followed by a short column of the Pierce type.[2] The injector area is laid out to house three separate injectors, each including a Cockcroft-Walton, ion source, and accelerating column. Because of the three injectors, rather long transport systems lead to the first linac tank.[2] The three beam transport systems merge to inject into the linac as shown in Fig. 7. At present, injector A, an H^+ source, is operational; injector B, an H^- unpolarized source, is being erected; and the third injector, C, is to be a polarized H^- source. Figure 8 shows the transition region at 100 MeV, where a path-length difference for H^+ with respect to H^- is introduced.

Because of the important physics to be done with polarized beams, the polarized ion source is very important to our project. A source of the Lamb-shift type was developed by McKibben, Lawrence, and Stevens, and is now operating at the Physics Division Van de Graaff. A source of this type is planned for LAMPF as soon as funding permits. It is estimated that the complete polarized ion system into the linac will cost about one-half $M.

The high-intensity, high-duty-factor H^+ ion source and the 750-keV accelerating column have been operating since June 1970, and quite a bit of experience has been gained.[2] The duoplasmatron H^+ source has operated for over a year (3000 h), and has required only the replacement of a cathode during this time. This is particularly gratifying since the duoplasmatron lifetime at a high duty factor was originally considered to be a serious problem. The H^+ system was injected up to 28 mA into Tank 1 of the linac at 15 $\sec^{-1}$ and 100 μs pulse length.

The column has operated reliably for two years. Cockcroft-Walton dome arc-downs are a problem we encounter at the higher power levels, at the rate of one every half hour or so.

It is planned to accelerate H^- and H^+ beams simultaneously in the linac. The H^- injector is the charge exchange type. A beam of H^+ and H_2^+

ions is extracted from a duoplasmatron source, at an energy of 15-30 keV. The charge exchange takes place in an exit canal through which passes H_2 gas from the duoplasmatron. Present performance of the latest developmental H^- source is as follows: H^- current, 300 μA; transverse emittance, 2.5 πcm-mrad (750 keV equivalent).

The H^- Cockcroft-Walton supply and dome are installed. Assembly of the accelerating tube is complete. Assembly of the accelerating column is in process. Half of the H^- beam transport line is installed and aligned. Before the H^- source is operational, the following remain to be done: 1) to complete the column assembly and the mating to the dome; 2) to install the H^- source in the dome; and 3) to complete the transport line. This should be done in the next few months.

Drift-Tube Linac

The four tanks of the post-coupled drift-tube linac, which produce 100 MeV, have been in operation with beam since the spring of 1972. Figure 9 is the inside of the post-coupled linac. Figure 10 shows the outside of the tanks. Very few serious operational problems have been encountered. Vacuum leaks at the articulating flange or spacer between tanks 1 and 2 were encountered and repaired. The ceramic dome windows at the rf power feeds on tanks 2, 3, and 4 have proven unsatisfactory because of pinhole defects in the ceramic. The domes have all now been replaced by 14-in. Rexolite windows.

We suspected a misalignment of some of the tank 1 quads during the initial operation because tank 1 demanded a strongly steered input beam as revealed by a steering optimization procedure. Optical checking later revealed large misalignments of four quads in tank 1. After realigning the quads, no steering is required for injection into tank 1.

Tube Experience

The main 201.25-MHz triode amplifiers, utilizing the RCA-7835 triode as the final stage, by now have 1122 h of operation average for each of the seven live tubes. We have encountered one failure during this time; that tube lasted 616 h. These are insufficient data to say much about the expected life. The 4616 Driver stages have had three failures; the average life of these three was 805 h. The eight survivors have an average of 2081 h of service. The data for the 805-MHz tubes are shown in Table I.

Beam Loss

During the design of LAMPF we were concerned about the problem of beam loss in the linac. A localized accidental loss of even 1% of the full beam (10 μA av) would produce catastrophic local heating and unacceptable radiation levels in the rf sector buildings above, so this must be controlled by the fast shutdown system. But, beyond that, we have set 1 μA total loss through the linac as the design upper limit of beam loss during regular operation, i.e., 0.1% of full beam. A great deal of study of beam steering and beam quality has been carried on in the last few months, following 800-MeV operation, by Swenson, Crandall, Paciotti, Stovall, and others. The following recent results are very encouraging.

A 100-MeV beam was run into the "north port" 45° diagnostic line with the following parameters: (1) 2.8 mA peak current; (2) 200 μsec beam width; (3) 120 pps for an average beam current of about 70 μA.

The average amount of beam lost in the transition region of about 70 μA conditions was less than one part in 10^3, i.e., >70 nA. The spill in the drift tube was even less. The linac was operated for 5 min at 70 nA, and for ∿ 45 min at 35 nA. The

TABLE I

TUBE LIFE DATA-805 MHz

Type	Alive no.	Av h alive	Dead no.	Mean time to fail	Expected life
LPT-44	76	1367	2	798	7000
VA-862A	46	1960	5	3074	6350

Note: Litton - insufficient data but worse.

limitation at present and for some time to come should be not in the linac but in the power capacity of the beam stop and targets.

Fast Phase and Amplitude Control

LAMPF requirements on phase and amplitude were somewhat special because of the long pulse, high beam loading, and the fact that we operate in a stable phase region which means that phase and amplitude errors drive phase oscillations. The fast phase and amplitude control system design began in June 1963. Two years later a detailed analysis had been done and considerable work with prototypes was done. The tolerance adopted was 1% on the amplitude and ±2 deg in phase, during one pulse. The reference frequency is generated by a crystal oscillator, multiplied up to 201.25 MHz and to 805 MHz for the two power amplifier systems. The signal picked up from the tank (module) is compared to the reference by a fast phase bridge, the error signal amplified and used to control the drive voltage. To make absolute phase settings in the first eight modules of the 805 sector, a time-of-flight method on the centroid of the beam (called the ΔT method) is used as described by Crandall et al in Session F at this conference. This method aided materially in setting up the linac prior to the first 800-MeV runs. The full potential for a stable narrow-energy beam is still to be developed as we work with the beam.

Central Computer Control

Very early in the design of LAMPF the decision was made to have commands and data in the central control room handled exclusively through a digital computer. Figure 11 shows the control computer with Sally Shlaer at the console, and in the background one of the two consoles for operating the linac. The decision for complete computer control was taken with some trepidation, since at that time it was not completely obvious that the system would be tractable in terms of cost and complexity. As time went by, the system steadily improved in reliability and power. The general trend toward more computer per dollar has certainly been helpful. Equally important, however, has been the development in house of a powerful library of systems and applications programs. The flexibility and power of the computer control system has been vividly demonstrated. During the turn-on of the accelerator, the operators have used, to a great advantage, the programs designed for automatic turn-on of rf modules, for automatic beam steering, search routines for automatic phase and amplitude tank adjustment via ΔT measurements, and the variety of the alphanumeric and graphical displays.

As mentioned in the fast phase and amplitude section, for the initial adjustments of the amplitude and phase it is not possible to set the tank phases accurately enough without using the beam itself. For example, to set the relative phases of two adjacent tanks correctly to one degree would mean setting equivalent free space-length differences of the waveguide correct to 1 mm.

Measuring the shifts in arrival time of the beam centroid at a few points along the linac with the nth tank on and off was the basis of a method devised two years ago by Crandall and Swenson, using the first order equations for the longitudinal motion of the beam. So many measurements are involved that it would have been tedious and time-consuming to do manually. The computer used this ΔT turn-on procedure to adjust the phases and amplitudes of modules 5-12, which greatly expedited the 800-MeV test.

Adjustment of the modules beyond number 12, using the ΔT method becomes progressively harder as beta increases. We plan to employ alternatively a beam-momentum determination, using magnetic deflection in the so-called beam line X north of the switchyard. The first measurements by Shively on a 211-MeV beam gave the following results:

Nominal beam momentum	664.85 MeV/c
Nominal beam energy	211.68 MeV
Nominal line X dispersion at LX II-02	1.5 cm/%
Measured momentum (±0.1%)	665.8 MeV/c

The modules 5-12 had been preset by the ΔT method, with a precision $\Delta p/p \sim 0.3\%$. The measured sensitivity of energy to phase in module 12 was 0.017 MeV/deg compared to the estimated value of 0.02 MeV/deg. It appears that the line X spectrometer and the ΔT method will be complementary for linac adjustment.

Beam steering algorithms were written to search for optimum settings of steering winding currents, in terms of profile monitor measurements. They have been very effective, for example, in setting steering and focusing in the 100-MeV transition region.

Experimental Area

Because of the very high reactivity in the LAMPF beam, the design of the experimental area differs in important ways from the experimental floor of a typical large accelerator. The requirements for remote-handling, resistance to radiation damage, and heavy-shielding capability extend beyond the targets themselves to close-in secondary beam magnets, vacuum flanges, and other vacuum plumbing, magnet connections, main beam-transport magnets, radioactivity in the cooling water, and so on. Components, which for a less powerful accelerator could be fabricated and installed with a minimum of design, must be carefully engineered for LAMPF. Figure 12 shows the experimental area layout. The high-power H^+ beam from the linac goes through the switchyard through area A with target cells for producing secondary pion beams. Figure 13 shows area A and the beginning of the shield. From there it goes to the isotope production section, a future on-line mass separator, the biomedical pion line, ν area, and the beam dump.

The system for remote handling in area A is based on a 30-ton bridge crane for stacking shielding and moving magnets, etc., a hot cell area, plus a special purpose vehicle called Merrimac, Fig. 14. Merrimac is a vehicle designed for remotely disconnecting and connecting radioactive components and transporting them to a hot cell area. It consists of a steel box, carried by a gantry, on which an operator rides and controls manipulators to perform the actual connects and disconnects. Merrimac will not be used in the first phase of the experimental area operation since the full shield height will not be stacked. The full shield weighing 42,000 tons includes 25,000 tons of steel, the rest concrete. Don Hagerman is chairing the Experimental Area Steering Committee.

The goals for the primary and the secondary beam lines are as follows:

April 1 - 1 microamp beam to area A

In area A, two target stations and four secondary channels, namely, low pi, stopped μ, P^3, and EPICS to be operational

Beyond area A the beam to continue to the biomed target and the beam dump

The biomed channel to be operational

H^- beam to beam line C, HRS, and area B. HRS operational

September - EPICS spectrometer operational

After April we plan to gradually increase the level of beam intensity, reaching the full design power in January 1974.

Experimental Program

Albert Einstein once remarked, "A perfection of means and confusion of aims seems to be our main problem." For LAMPF, we must keep our eyes on the goal: The advancement of knowledge of nuclear science and related disciplines. The experimental program must now receive priority as the facility begins to reach completion. The use of the facility by LASL and outside scientists is developing according to plans detailed in the "Blue Book."

One hundred and thirty-seven proposals had been received as of the end of September. Of the first 115 proposals, there were 86 LASL participants, and on the average each was involved in two experiments. Outside of LASL there were 250 participants, each on the average involved in two experiments. MP staff were spokesmen for 15, other LASL four, and outside institutions had 96 spokesmen. So the research participation is broadly distributed.

The experimental program includes the following:

HRS - Elastic and inelastic scattering of p from N, search for ABC, Pπ reactions, quasi-free scattering

EPICS - Elastic and inelastic scattering of π from N, πP reactions, π double-charge exchange, π forward scattering, search for πc

Low Pi - πP scattering, σ_T, π charge exchange, πN scattering

P^3 - Rare decay modes of the π,π form factor, $\pi P \rightarrow 2\pi P$, π^-D elastic, (π,πn) reactions, polarization parameters in πP scattering

Stopped μ - Muonium, μ capture, γ spectra, μ X-rays, μ and π atoms, μ chemistry, μ capture in H and D

Nucleon (B) - pp spin correlation, p + d → neutron +, neutron total cross sections, studies with polarized beams and polarized targets

ν - The LAMPF beam stop is an intense source of neutrinos. The neutrino physics program includes a test of the form of the law of lepton conservation, neutrino-electron scattering, and a test of the Davis experiment to detect neutrinos from the sun.

An important part of the program will be concerned with applications to nuclear science. This includes radiation damage studies using the beam dump, isotope production, and applied use of neutrons. In addition, technology spin-off -- both for accelerators themselves and spin-off of special techniques will be encouraged. The applied program for which we have the highest hopes is the biomedical program, looking toward the use of π^- in cancer therapy. Since this program has been extensively discussed at other recent conferences, the most recent being last week, here I will only remark that we are making a determined effort to have the biomedical channel operational early next year.

REFERENCES

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2. D. W. Mueller, E. A. Meyer, R. R. Stevens, Jr., B. C. Goplen, M. A. Paciotti, and C. R. Emigh, "Operation and Performance of the High-Intensity Proton Injector of LAMPF," Proc. 1972 Proton Linear Accelerator Conf.

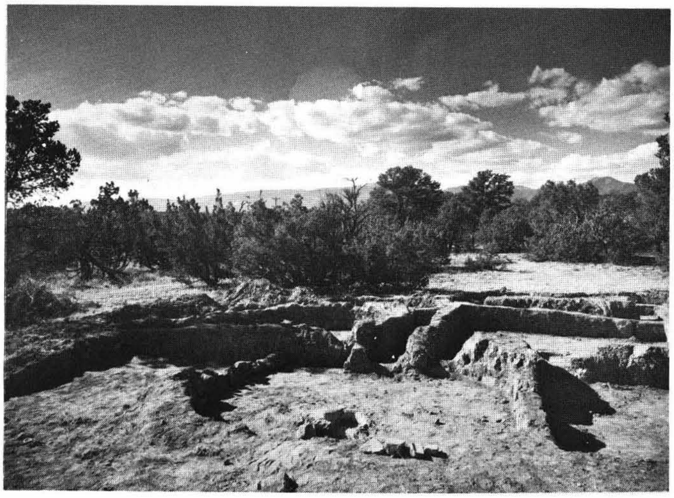


Fig. 1 LAMPF Site before construction started

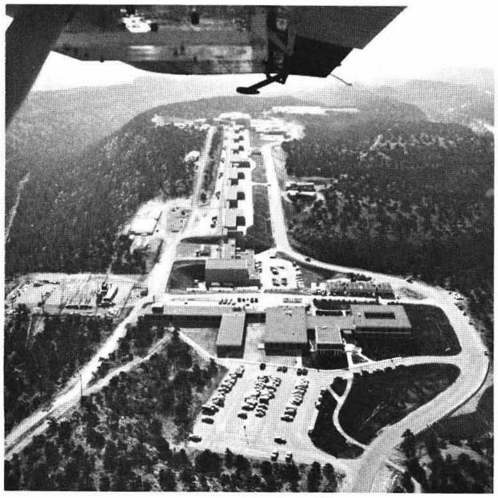


Fig. 2 LAMPF Site as it now looks

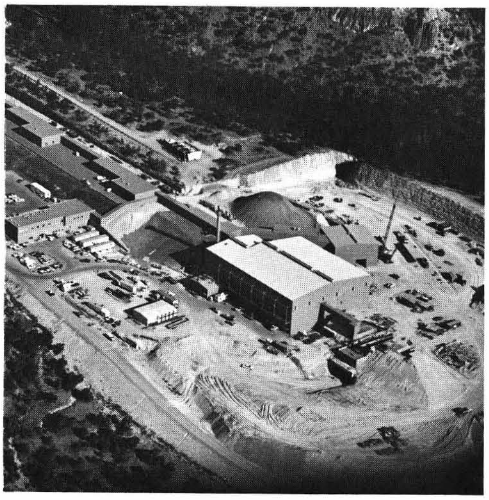


Fig. 3 Experimental Area: HRS, meson area, and biomedical area

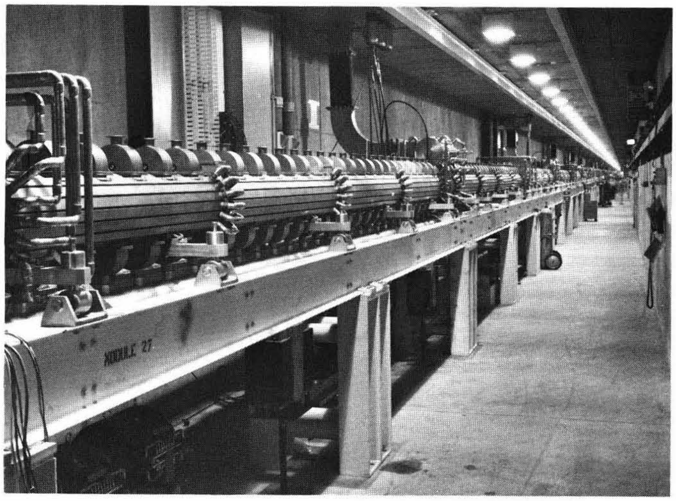


Fig. 4 Waveguide linac

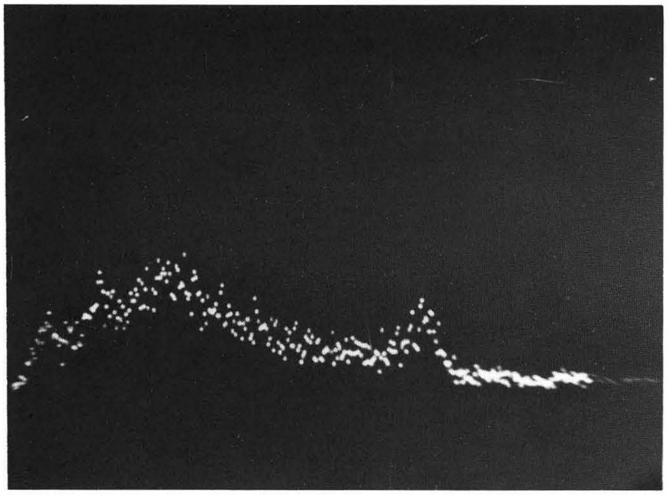


Fig. 5 A knock-on delta-ray spectrum demonstrating first 800-MeV operation.

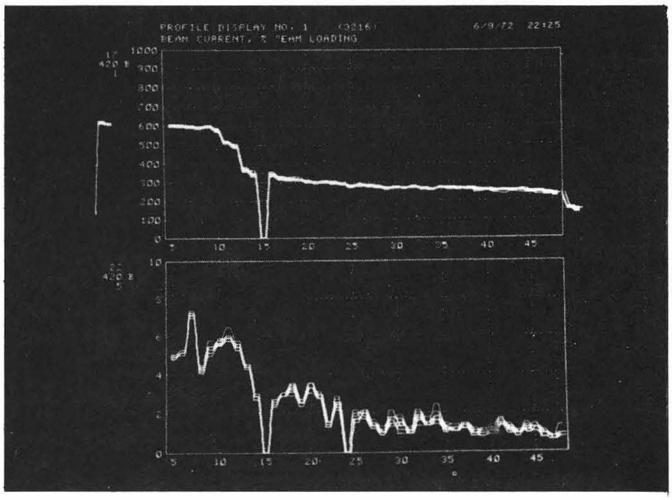


Fig. 6 Beam current and beam loading along linac for first 800-MeV turn-on.

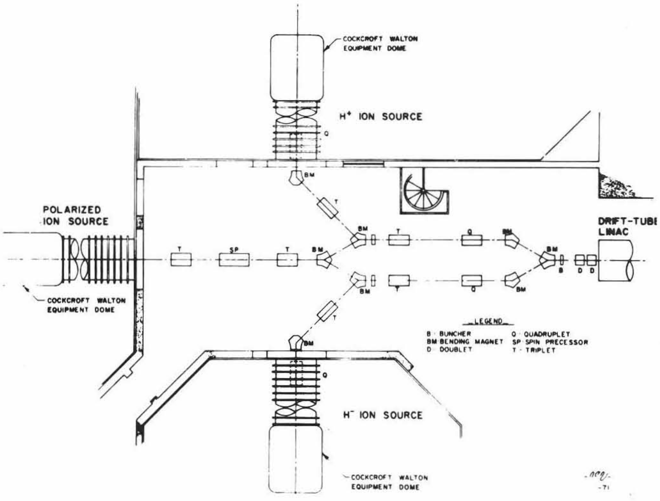


Fig. 7 Three beam transport systems merge to inject into the linac.

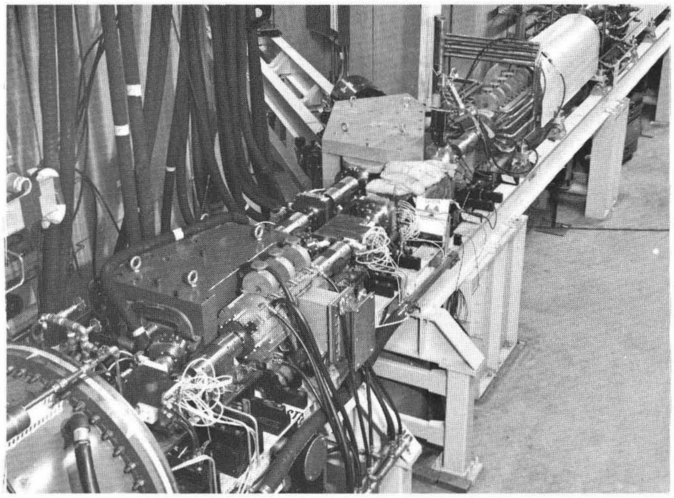


Fig. 8 Transition region at 100 MeV, introducing a path-length difference for H^+ with respect to H^-.

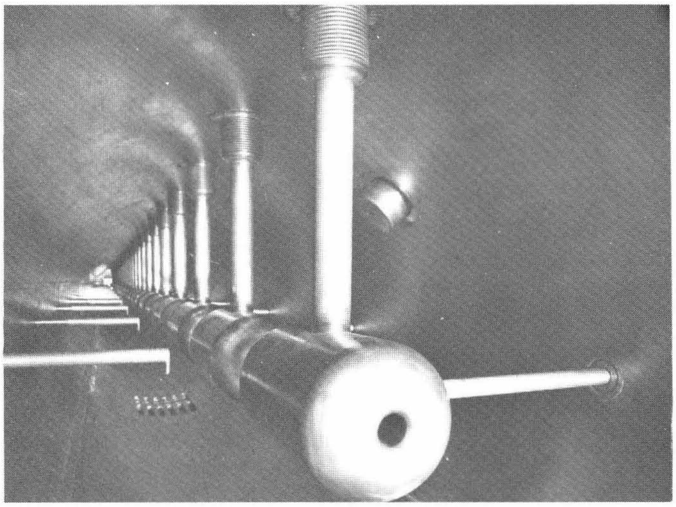


Fig. 9 Inside the post-coupled linac.

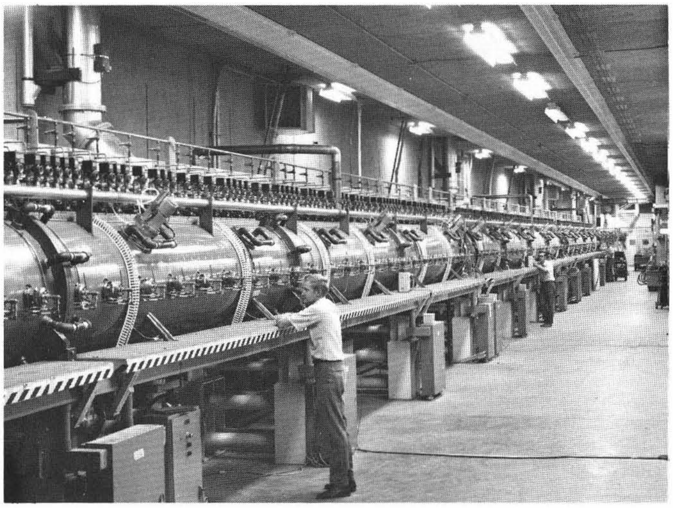
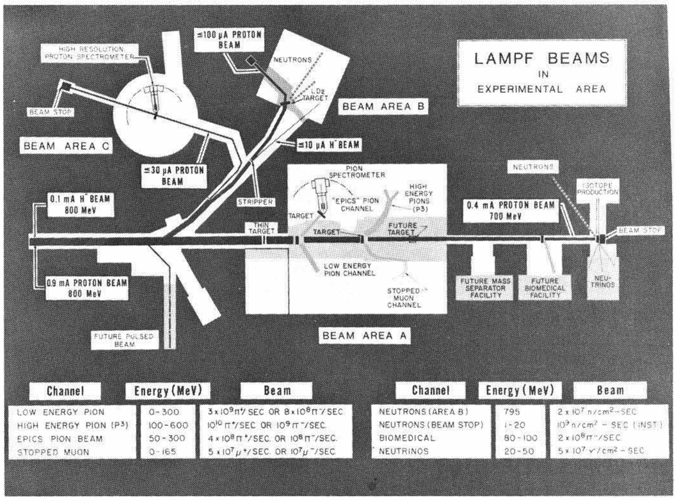


Fig. 10 Outside of the tanks of the post-coupled drift tube linac.

Fig. 11 Central control computer.



Channel	Energy (MeV)	Beam
LOW ENERGY PION	0-300	$3 \times 10^9 \pi^+$/SEC OR $8 \times 10^8 \pi^-$/SEC
HIGH ENERGY PION (P³)	100-600	$10^{10} \pi^+$/SEC OR $10^9 \pi^-$/SEC
EPICS PION BEAM	50-300	$4 \times 10^8 \pi^+$/SEC. OR $10^8 \pi^-$/SEC.
STOPPED MUON	0-165	$5 \times 10^7 \mu^+$/SEC. OR $10^7 \mu^-$/SEC

Channel	Energy (MeV)	Beam
NEUTRONS (AREA B)	795	2×10^7 n/cm²-SEC
NEUTRONS (BEAM STOP)	1-20	10^9 n/cm² - SEC (INST.)
BIOMEDICAL	80-100	$2 \times 10^8 \pi^-$/SEC
NEUTRINOS	20-50	$5 \times 10^7 \nu$/cm² - SEC

Fig. 12 Experimental area layout

Fig. 13 Area A and the beginning of the shield.

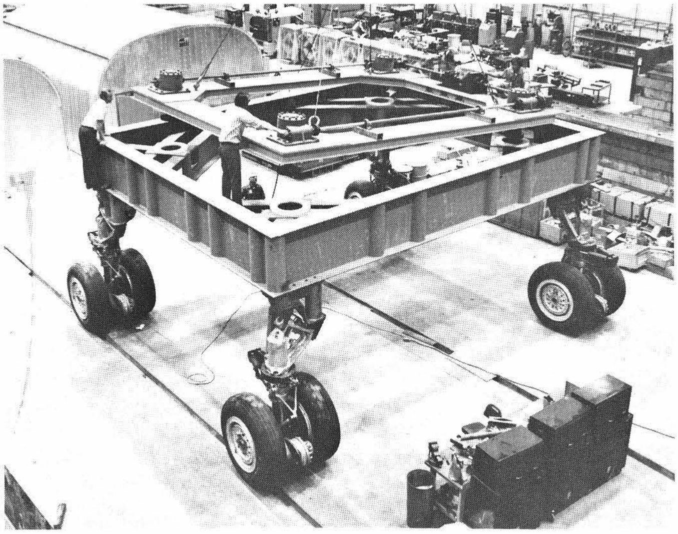


Fig. 14 System for remote handling in Area A, the Merrimac.