OPERATING RESULTS ON THE 800-MeV PROTON LINAC AT THE LOS ALAMOS SCIENTIFIC LABORATORY*

by

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Introduction

The accelerator[1,2,3] at the Clinton P. Anderson Meson Physics Facility† is a linear proton accelerator with the very high design average current of 1 mA, a maximum energy of 800 MeV and an initial macroscopic duty factor of 6%. The accelerator is about 1/2 mile in length; an aerial view of the facility is shown in Fig. 1. The machine is designed to accelerate simultaneously both H^+ and H^- ions; eventually a polarized H^- beam will also be available. The first stage of acceleration from the ion source to a kinetic energy of 750 keV is accomplished using a conventional Cockcroft-Walton high voltage generator; separate high-voltage sets will be used for each ion species. The 750-keV beam is injected into a post-coupled drift tube linac which accelerates the protons to 100 MeV. From 100 to 800 MeV a side-coupled accelerator structure operating in the $\pi/2$ mode is used. The drift tube portion of the accelerator operates at a frequency of 201.25 MHz with a peak rf power demand of ~10 MW; the side-coupled portion operates at 800 MHz with a peak rf power requiremnent of ~44 MW. The entire accelerator is controlled and monitored through a comprehensive computer control system.

Physical construction of the facility began on Feb. 15, 1968, with a ground breaking ceremony for the Equipment Test Laboratory building. The first 800-MeV beam was produced on June 8, 1972, a few weeks ahead of the date scheduled several years earlier. The final construction cost is about $57 million which is only slightly higher than the original $55 million estimate; this is a significant achievement in view of the severe cost escalation during the construction period and the substantial increase in the experimental facilities over the original design.

The primary purpose of the facility is the experimental study of various aspects of nuclear science and related disciplines. This work cannot start in full measure until both the experimental facilities and the accelerator are in operation. Much work remains before the experimental areas are complete; however, initial tune-up of the primary and secondary lines in the experimental area can begin in the late spring of 1973 with greatly reduced current (~1 μA) from the accelerator. Thus, we have chosen to emphasize experimental area work at the expense of a somewhat reduced rate of development on accelerator problems. Nonetheless, work on the machine has produced many gratifying results and we have every expectation that the accelerator will be successful in fulfilling the experimental program requirements on the appropriate time scale.

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†LAMPF (Los Alamos Meson Physics Facility) was formally dedicated as the Clinton P. Anderson Meson Physics Facility Sept. 29, 1972; this was done in recognition of Senator Anderson's long-term interest and support of nuclear science and related fields.

Integrity of Design

Sufficient operating experience has been gained with the different machine components so that we are starting to have some real measure of the adequacy of their design and construction. In general, this experience has been good and most problems encountered have been of a routine nature. There has been no indication of the need for any major hardware retrofits. As might be expected, new demands on accelerator instrumentation and better evaluation of original design have led to continuing development in this area.

Much of our early concern about accelerator reliability was connected with the rf systems. Experience with klystrons used at 805 MHz has been good; we have accumulated some 150 kh of experience on these tubes and the anticipated mean time to failure is in excess of 7000 h. All of the 805-MHz rf system and accelerator structure has been tested at 12% duty factor and appears to operate satisfactorily; thus, it should be well behaved for the initial 6% duty factor operation. The 201.25-MHz rf system is difficult at high average rf powers, our present experience indicates that the existing system is probably adequate for 6% beam duty factor but it is unlikely that it can be pushed to 12% without major modification.

The choice of a comprehensive computer control system for the facility was correct. It provides us with the necessary monitoring and control of some 6000 binary data channels and 2500 analogue data channels. Equally important, it provides us with a very sophisticated and necessary tool for complex studies of accelerator performance. The long-term reproducibility of the data channels as well as the apparatus is a matter of continuing study via the computer and repeated measurements of beam parameters. An area of continuing development in the control system is the hardware and software operating system of the computer. As more of the accelerator comes into routine operation and the sophistication of the application programs increase, a continuing effort is required to correct system defects which precipitate stalling of the computer. Progress on this problem is keeping abreast with the ever-increasing computer burden. The net effect is a control system availability of 90-95%. This problem will eventually yield.

The Tuning Problem

The primary goal in tuning this accelerator is to produce a beam of the requisite energy and current in such a way that beam loss does not cause appreciable damage to the accelerator. This problem is very difficult in a high average current machine; for example, we believe on the basis of activation calculations that we can tolerate a beam loss of only 1 μA average current in that portion of the machine between 100 and 800 MeV - this is a loss of only 1 part in 10^3 of the full design current. Using this loss criteria and beam dynamics calculations, adequate control, manufacturing, and alignment tolerances were determined during the design of the machine. In general these tolerances are tight but within the state-of-the-art; as examples, phase of the rf accelerating field must be controlled to ~2°, its amplitude to ~1%, and the lateral postion of the quadrupole doublets used for focusing must be controlled to ~0.010 in.

A complication in the tuning problem is its changing character along the machine. This is displayed in Fig. 2 which shows the phase oscillations/module as a function of module number (a single module generally represents the shortest length over which we can control phase, amplitude, steering, and focusing). In the low energy portion of the machine one or more oscillations occur within a single module; the converse is true in the high energy portion. Thus a variety of tuning techniques are needed in the various portions of the machine. Some of the more important techniques are discussed below.

The simplest method of tuning which we use is to observe the beam loading in a single module as a function of rf phase and amplitude. One can, under normal conditions, use this technique to get a portion of the beam accelerated and module by module accelerate some beam through appreciable portions of the machine. In fact, beam loading was the technique used to produce the first full energy beam. The difficulties with the method lie in making good measurements of rf power and having an adequate knowledge of beam bunch parameters and energy entering the particular module. A graph of a measurement of beam loading and some beam loading calculations[4] is shown in Fig. 3; the data were taken under very good conditions. It seems unlikely that one can ever do more than achieve approximate phase and amplitude settings using this technique.

In the early part of the machine where one or more phase oscillations are contained within a single module it is possible to determine the phase and amplitude set points with adequate precision by measuring that fraction of the current accelerated to the appropriate energy as a function of rf phase and amplitude. The experimental data fit the calculated curves quite well.

In that portion of the machine in which a module contains ~1/2 phase oscillation it is possible to determine the correct phase and amplitude by transit time measurements.[5] These measurements include a determination of the transit time through the module in question both with the field "on" and "off" as well as the time required to drift through the following module. This method also gives a very precise measurement of the energy of the beam entering the module (the indicated accuracy is better than 0.1%); thus it also checks some aspects of the performance of the earlier portions of the machine. An essential feature of this measurement is that it determines some of the characteristics of the motion of the beam bunch within the acceptance bucket of the accelerator. The development of the necessary electronics and microwave gear for this measurement has been challenging; the present situation is that a module can be accurately and reproducibly set up in 5-10 min.

In the higher energy portion of the accelerator there is only a small fraction of phase oscillation within a single module and it is adequate to make a precision measurement of the output energy of the particular module as a function of rf phase and amplitude. This is done using a portion of the beam switchyard as a precision spectrometer; an absolute measurement of the momentum to 0.05% is required. This again is a complex instrument which is computer-controlled and will eventually have on-line data reduction. It has required substantial development but present results are encouraging. Preliminary measurements of the momentum spectrum of the accelerated beam at several different energies are shown in Fig. 4. From these spectra it appears feasible to make the required momentum measurement.

The tuning of the injector and beam transport system to the machine has been described elsewhere.[6]

Radial position and size of the beam within the machine is measured by the current generated in a thin (0.005 in. or less) wire which intersects a portion of the beam. These wires are either motor driven and move through the beam (wire scanner) or there are many (40-60) in fixed arrays which can be inserted into the beam. With the aid of this type of data it is possible to both steer the beam and match the quadrupole doublet strengths to the beam emittance; typical wire scan results are shown in a reference.[7]

More precise steering of the beam is accomplished using the beam spill monitor system. This system presently consists of ~60 radiation detectors distributed along the accelerator which automatically turn off the beam in case of excessive spill. Their output can be displayed and used for fine tuning on the steering. An automatic method of on-line calibration using the beam has been develped. Improvements to this system which will increase its flexibility are being constructed.

In summary, a variety of different tuning techniques are necessary. All of them require extensive data analysis and highly developed hardware. A major effort has to be spent on tuning problems with low current beams before one attempts high current operation.

Interim Results

In the 8-month period following the completion of construction of the accelerator (July 1972 through Feb. 1973) our principal concern has been the development of the tuning procedures which are partially described above. Of almost equal importance has been the development of effective operating and maintenance staffs. The development of the maintenance and operating capability is in many ways essentially an administrative problem. Efficient, well-trained and highly motivated staffs must be assembled. Adequate data bases must be developed to maintain good control over maintenance activities and permit systematic evaluation of maintenance problems. Substantial progress has been made on this general class of problems; however, it is too early to make a quantitative evaluation of our work in this area. Nonetheless, a gratifying increase has been made in the number of hours of scheduled operation per month (currently ~400 h/mo) and the availability of the beam for useful purposes.

Some quantitative evaluation of the technical progress in tuning the accelerator can be made on the basis of Tables I and II which display the maximum peak and average current levels which have been studied. Note that the maximum peak and average values of current were not achieved at the same time; rather they are the results of separate experiments. It must be emphasized that the limitation on the maximum value of average current is set by simple beam loss (i.e., scraping along the walls of the accelerator). It should also be noted that due to budgetary limitations we have imposed a limit on the maximum energy of 500 MeV during FY 1973.

TABLE I

Maximum Observed Peak Currents

Energy (MeV)	Peak Current (mA)
0.75	40
100	15
212	15
302	6
400	3
800	~ 1

These currents all involve pulse lengths of 100 to 300 μsec. The apparent decrease in peak current at higher energies is misleading; it is not the result of any physical phenomena - rather it is the result of insufficient time to study high peak currents at high energy. There is no evidence of any exotic phenomena such as "beam blow-up" under any operating conditions which have been used.

TABLE II

Maximum Observed Average Currents

Energy (MeV)	Average Current (μA)
0.750	2,400
100	310
212	59
302	11
400	3-4
800	~ 0.1

Again, the apparent decrease in current with increasing energy is misleading - these are interim results. The 310 μA produced at 100 MeV was extracted from the machine at the 100-MeV point and transported to a separate 100-MeV beam dump. The currents for the higher energies were transported to temporary beam dumps in the switchyard at the end of the machine. The limits on the 100-, 212-, 302- and 400-MeV beams were set by radial beam spill at the time of the experiment. In any module above 100 MeV a beam loss on the order of tens of nanoamperes average current automatically limits the average current.

Transmission through the machine, as measured by current transformers in each module, displays no abrupt steps when the machine is properly adjusted. Overall transmission through the accelerator (after the region of initial beam capture) in excess of 99% has been observed (212-MeV energy). At this time, it is difficult to maintain a calibration precision of greater than one or two percent in the current transformer system. Thus further improvements in transmission will probably be based on radiation measurements of beam loss.

The emittance of the 212-MeV beam has been measured at the end of the accelerator and typical rms values are $\pi/10$ mr-cm. This value is comfortably smaller than the π mr-cm which is the acceptance of the early portion of the switchyard and experimental area transport system. This measured value is also well within the predicted value for the machine.

The energy spectrum of the beam (Fig. 4) typically indicates an upper limit on the FWHM value of ~0.25% $\Delta p/p$. If the spectrometer is tuned more carefully one can observe a FWHM of 0.12% $\Delta p/p$ at 302 MeV.[8] Either value is comfortably within the predicted value and bodes well for the eventual success of those experiments requiring a small $\Delta p/p$ in the primary beam.*

Future Plans

The immediate problem of interest is the acceleration of H^- ions. The H^- ion source has been constructed and tested; installation work in the Cockcroft-Walton enclosure is nearly complete. By late March 1973, we should be testing the H^- beam in the accelerator. Shortly thereafter we should begin the study of the simultaneous acceleration of both H^+ and H^- beams.

The problem of raising the beam intensity will undoubtedly occupy our interest for many months. The principal thrust of our work is to exploit to the fullest the minimization of beam loss by fine tuning the focusing, steering, and rf. It may be feasible to prepare a better beam for acceleration by further optimization of the injector and beam transport from the injector to the accelerator. If these approaches do not fully satisfy our requirements, it will be possible to add one or more collimators along the accelerator to concentrate any beam loss in suitably shielded and constructed hardware.

The construction of the experimental area will continue for several months. By late spring or early summer several primary and secondary beam lines will be ready for preliminary studies at low average currents (1 μA or less). By late fall the experimental areas will be sufficiently developed so that H^+ beams of 10 to 100 μA will be needed. An H^- beam of 1 to 10 μA should be sufficient until late in 1973 or early 1974. It is likely that early in 1974 the H^+ experimental program will start to need average currents in the 100-μA to 1-mA range.

The enrgy of the machine will be limited by administrative decision to 500 MeV or less until July 1973. Thereafter the energy will be increased to the maximum of 800 MeV as higher energies are needed. We believe that this increase in peak energy will be straightforward.

A very modest number of exposures for nuclear chemistry research[9] have been made during the past few months. This effort will grow and soon be joined by many other research programs. The overall scale of the experimental program is large; for example, some 82 proposals have been approved for a total of ~16,000 h of beam time on the eight or more secondary channels.

We believe that all the evidence to date indicates that the design and construction of the accelerator 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.

Acknowledgment

The author deeply appreciates the very effective work on the design, construction, development, and operation of this facility which has been done by many different people at the Los Alamos Scientific Laboratory.

*A small $\Delta p/p$ is important to the eventual success of our High Resolution Spectrometer Facility.

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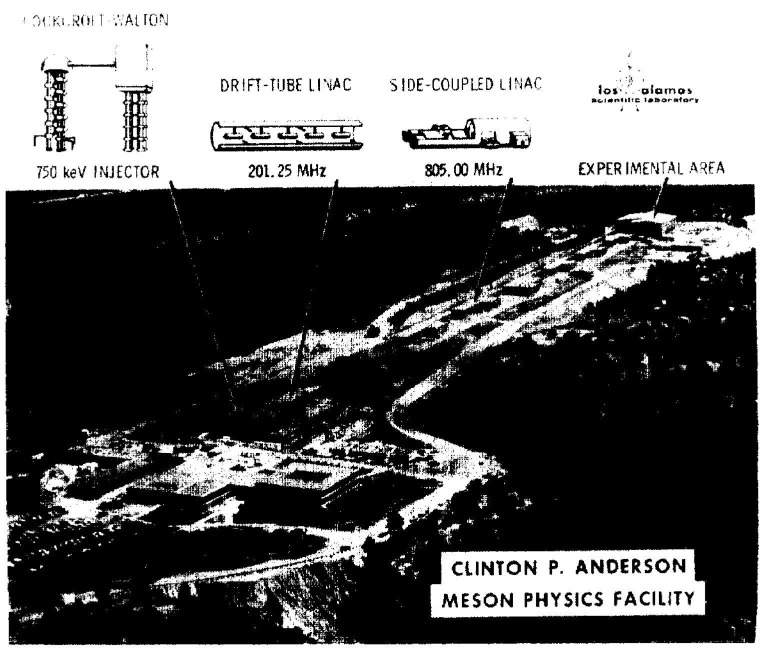

Fig. 1. An aerial view of the Clinton P. Anderson Meson Physics Facility. The length of the accelerator is ~1/2 mile.

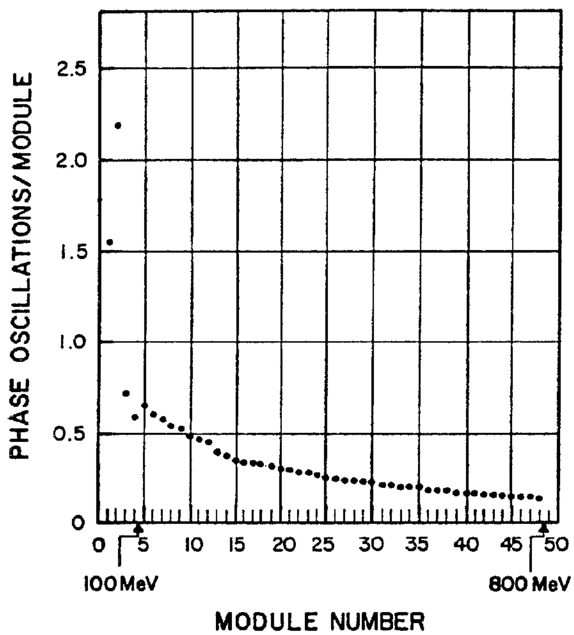

Fig. 2. Phase oscillations per module as a function of module number. The optimum tuning technique for setting the phase and amplitude of the rf field is determined by the magnitude of the phase oscillation within the module.

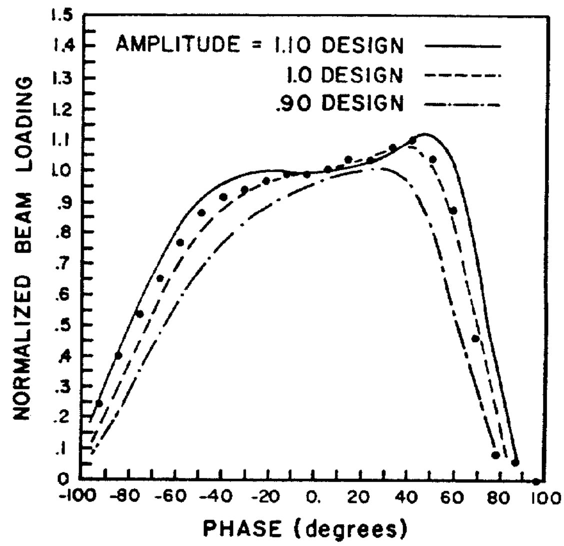

Fig. 3. A very good set of data for beam loading in module 12 (212 MeV). This data displays the difficulty even under ideal circumstances in using this technique to determine phase and amplitude to the required precision (2° and 1% respectively). The calculated curves are based on what we believe are realistic beam bunch parameters.

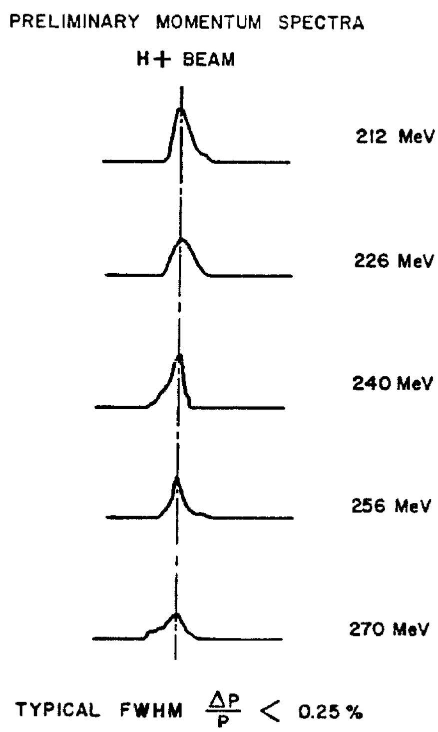

Fig. 4. A preliminary set of momentum spectra. Later results have shown that these widths are upper limits on the true spectra.