LAMPF OPERATIONS AT 500 μA*

D. C. Hagerman
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87544

Summary

LAMPF now operates reliably producing 500 μA of H^+ beam and a few μA of H^- beam or 10 nA of polarized H^- beam. Beam loss in the accelerator is quite acceptable at these currents. This level of performance has been achieved through solution of a wide variety of accelerator problems and a continuous evolution of the experimental areas. The future of the facility is promising both in terms of the existing experimental programs and the opportunities for significant facility improvement projects.

Introduction

The Los Alamos Meson Physics Facility** (LAMPF) accelerator has matured in the sense that it runs reliably at significant currents and apparently can fulfill all of the expectations of its designers and builders. In addition to the high-current beam a low-current H^- beam is simultaneously produced. This combined operation satisfies the needs of a very broad research program. It has taken more than seven years, after the first full-energy beam, to reach this level of performance. This rather lengthy time scale has many different causes including complexity of the accelerator, unprecedented beam currents, need for production operation pre-empting time for accelerator development, lack of adequate test dumps for high-current beams, and budgetary problems. Nonetheless, this machine has served the needs of the research program very well for several years in addition to being a major step in the art of accelerator technology.

General descriptions of this accelerator are given in several sources.[1,2,3] Briefly, the machine simultaneously produces H^+ and H^- beams at a maximum energy of 800 MeV. The H^+ ion source is duoplasmatron.[4] The H^- ions are provided from either a duoplasmatron charge-exchange source or a Lamb shift polarized source. Each source has its own Cockcroft-Walton machine to accelerate the ions to the 750 keV injection energy. Acceleration[5] from 750 keV to 100 MeV is accomplished in a drift-tube accelerator that is post coupled above 5 MeV; this operates at an rf frequency of 201.25 MHz. From 100 to 800 MeV a side-coupled accelerator is used operating at 805 MHz. The overall length of the accelerator is ∿780 m. Peak rf power required is about 50 MW. The macroscopic beam duty factor is 7.5% with 120 macroscopic pulses/s. The H^+ beam is the high-intensity beam and is used primarily for meson production. The H^- beams are low intensity and used for a variety of nucleon-nucleon or nucleon-nucleus research programs.

Progress in Beam Quality

A simple measure of our progress in beam quality is shown in Figure 1 which displays the relative beam induced activation (normalized to production current) of the high-energy portion of the accelerator as a function of H^+ production current. The beam induced activation has been averaged over many locations and long periods of time so it is a trend indicator rather than a measure of the quality of any particular beam.

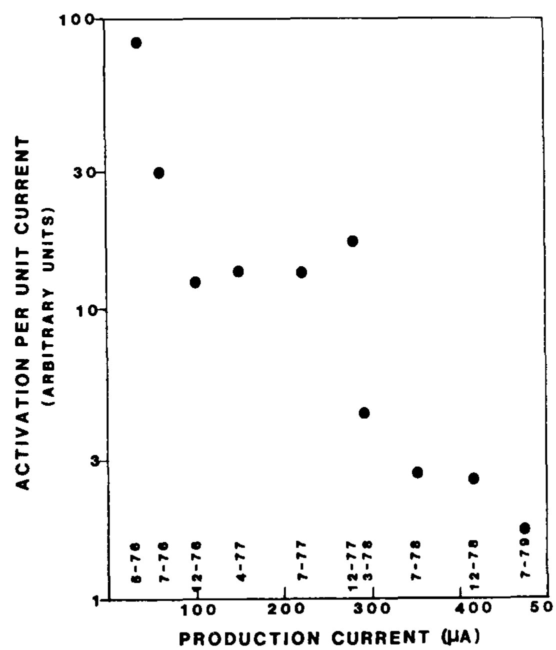

Fig. 1 A short history of accelerator activation and LAMPF average production beam current. Activation is the average of 67 separate measurements in the side-coupled linac between 240 and 800 MeV; each measurement is at a limiting aperture. The dates are a few weeks after start of production operation at that current.

* Work performed under the auspices of the Department of Energy.

** The formal name is the Clinton P. Anderson Meson Physics Facility located at Los Alamos, New Mexico, U.S.A.

If the emittance of the beam increased with current and the accelerator acceptance was unchanged during the period described by this figure, the activation would have increased faster than the current increased. Instead, this measure of beam loss dropped nearly a factor of 40 while the current was increased a factor of 13. This improved performance is the result of both reduced beam emittance at injection and improved acceptance of the accelerator.

The improvements in the emittance of the H^+ beam at injection have resulted from a variety of geometry and field changes in the source. In general, apertures are now smaller, hydrogen pressure and arc current are higher, and the extraction field has been modified from the original Pierce geometry. The result of these changes is that the emittance of an 8 mA beam is now about the same as that of a 2 mA beam a few years ago.

Improving the acceptance of the accelerator has been an iterative process since the first operation of the machine. One of the perplexing aspects of this development work has been the difficulty in determining, at any particular stage of development, the dominant cause of beam spill. This difficulty is caused in part by the very achromatic beam transport of the accelerator which can transport off-energy beam a long distance before it hits the wall of the accelerator and is detected by a spill monitor. For example, beam spill at that location in the accelerator corresponding to, for example, a beam energy of 365 MeV can be caused by any one or combination of the following: (a) improper adjustment or operation of any of the 24 rf amplifier accelerator structure subsystems upstream of this point, (b) some defect in injector operation or adjustment, (c) poor steering causing the beam to strike the wall at this location or be accelerated improperly at some upstream location, and (d) misadjustment of some quadrupole focusing element causing a large radial excursion in the beam envelope at this point. Any-one of these difficulties can be masked by some other compensating defect for that particular spill location; yet, when two things are wrong the overall machine acceptance is reduced even though some localized spill is improved. This extremely complex set of inter-relationships has been partially unraveled by many different development projects, nearly all of which required a significant effort in computer simulation of the beam in the accelerator. In addition, reliability and reproducibility of machine parameters has been greatly improved by diligent attention to the quality and performance of accelerator components. Some specific problem areas that have received attention are:

1. Comprehensive studies searching for the optimum longitudinal tune of the machine (i.e., optimum phase and amplitude values for the accelerating field) have been done. This problem has required development of very accurate techniques for measurement of beam properties since all accurate phase and amplitude setpoints are derived from observed effects of the field on the beam.

2. By using a combination of the beam as an indicator of misalignments and the best available surveying techniques, the machine has been systematically realigned.

3. The long (∿12 m) 750 keV transport lines connecting the injectors to the accelerator are troublesome since the beams have varying degrees of space charge neutralization along the transport system. Much of the tuning done in these lines is still very pragmatic in nature.

4. The general problem of matching simultaneously both H^+ and H^- beams is one of the major limitations in machine performance. These beams have different emittances and intensities at injection, hence, space-charge forces are different. Further, in the 100-MeV transition region, where the beams are spatially separated, not enough degrees of freedom are available to satisfactorily match both beams into the side-coupled linac.

A more quantitative measure of the degree of perfection of our present beams is that at 500 μA H^+ production current the beam lost between 70 and 800 MeV ranges from a few parts in 5000 to 2 parts in 500 with the typical value of 1 part in 1000. The off-energy portion of this beam that is lost in the switchyard is significantly less than 1 part in 10,000. When an H^- beam of 3 to 5 μA is accelerated simultaneously with the 500 μA H^+ beam, spill is increased in a minor way at a few locations.

Accelerator Tuneup

The procedures for complete tuneup are now very well understood with only a few exceptions associated with radial beam matching and optimization of drift-tube linac performance. Assuming that all equipment is operational and no major increase in beam current is planned something like three shifts are necessary for a complete tuneup. Six to nine shifts are usually scheduled for this activity at the start of a cycle since we continue to make changes in the ion sources or current on a cycle-by-cycle basis.

The reproducibility and stability of the equipment is now good enough so that a complete retune is required only three to five times a year. This reproducibility was strengthened significantly by the development of redundant methods of measuring and systematic monitoring of the most important accelerator parameters. By using all the information available, it is practical and routine to reproduce a satisfactory beam in short order even though one or more setpoints have been lost due to equipment failures. The control computer of course is essential in any tune-up operation.*

* The main control computer can be turned off during production without losing beam or any element of beam protection. Operation of one smaller computer is required at all times to maintain integrity of beam protection devices in the experimental area.

Some idea of the complexity of the tuneup can be gained from the brief listing of the more important tuning algorithms or measurement techniques given below. Nearly all measurements are processed through the computer which transforms the data into some easily understood form.

Transverse Tuning

1. Emittance measurements[6] provide beam size, orientation, centroid position, and centroid angular information that is used as input to matching and steering programs so that the beam is properly focused and steered into the accelerator.

2. Wire scanners provide beam position and size information used for steering and check of radial match. Beam position can also be measured by a nonintercepting system.

3. Experimental area beam profile measurements are made with harps or wire scanners.[7]

4. Experimental area main beam-line magnets are set up using a computer algorithm that cycles the magnets to selected field strengths.

Longitudinal Tuning

1. Drift-tube accelerator phase and amplitude setpoints are determined from phase-scan measurements that are compared with computer simulations. These measurements also include a differential phase scan to measure phase width of the beam entering the side-coupled linac.

2. A beam energy measurement using a time-of-flight method based on rf measurement techniques in combination with a detailed simulation of the side-coupled linac is used to determine phase and amplitude setpoints between 100 and 800 MeV. This is the only fully automated closed-loop tuning algorithm presently in use.

3. Energy width and low-energy components of the beam are measured in the switchyard where the beam transports provide energy dispersion. These measurements are particularly valuable in elucidating minor errors in the longitudinal tune.

Display Programs

1. A wide variety of computer displays are in use that present accelerator and beam parameters in a variety of formats. Graphical displays are particularly valuable when evaluating machine performance.

2. All important parameters are monitored; significant changes in value are automatically called to the attention of the operator.

Protection Methods

1. The usual sort of hardwired "run-permit" system controls personnel access and requires that the necessary equipment be "on" before beam can be turned on.

2. A "fast-protect" system[8] switches off beam on a 10 μs time scale in the event of malfunction of an rf amplifier, excessive beam loss, etc.

3. Beam transmission is continuously monitored by radiation detectors and differential current-measuring devices. These turn off the machine automatically if loss exceeds a predetermined value.

Beam Availability and Machine Reliability

During FY 1979 (Oct. 1978-Sept. 1979), production beam was scheduled for nearly 4600 h and long-term average beam availability was typically in excess of 80%. Of course, beam availability has wide variations from day-to-day. Difficulties that cause extended off periods (4 to 24 h) are infrequent; during the past year this level of difficulty has been caused by ion-source problems, control computer problems, major power outages, or some vacuum or rf-system fault in the drift-tube accelerator. Off periods ranging from a few minutes to 4 h are more frequent and are caused by minor vacuum failures, tube faults, or minor failure of some sub-system.

The availability of the experimental area plays an important role in overall beam availability; some of its particular problems are discussed below. Unfortunately, when a major experimental area problem arises its repair is frequently a matter of weeks which causes a major shift in schedules. Sensible definitions of beam availability in that circumstance are lacking. During FY 1979,we had one such incident that occurred between production cycles and caused a delay of the next production cycle for about two months.

Use of the facility is scheduled in terms of production cycles that have recently ranged in length from 8 to 15 weeks. In each production cycle, maintenance days (24 h total beam interruption) are scheduled on alternate weeks. Short development periods (12 h) are also scheduled on alternate weeks. Longer development periods are scheduled at midcycle and before and after each cycle. During the cycle, each week has on the average 132 h of production beam scheduled.

During the design of LAMPF, electron tube lifetime was a major concern and it was thought that this would be a strongly limiting factor on beam availability. Happily this has not been the case. Our latest information on tube lifetime is given in Table I for some of the more important tubes. The klystron information should be statistically sound due to the large amount of operating experience. In all cases, the data clearly displays a very satisfactory range of tube life.

The Experimental Areas

Successful operation and development of the accelerator is strongly dependent on the viability of the experimental areas. In turn, success of the entire facility depends on the vitality of the experimental program. It is inappropriate in this paper to discuss the experimental program but some description must be made of the experimental areas.

The most important features of the experimental areas[9] are those that permit simultaneous performance of 10 to 12 experiments. The H^- low-intensity beam is easily split into as many as three beams by change of charge state in thin foils; these beams are used either for direct interaction studies and/or for production of neutron beams.

The H^+ beam provides mesons in six secondary beam channels, is used for isotope production, and provides neutrinos from the beam stop. The beam passes sequentially through three targets, finally coming to rest in the beam stop. Time sharing is used to provide H^+ beam to a pulsed neutron facility. A high-resolution (50 keV) proton spectrometer and a high-resolution pion spectrometer (150 keV) are permanently installed. Two of the meson channels provide beam to multiple caves giving great freedom in scheduling use of these particular beams.

The overall utility of the H^- beams will be increased when the time-shared dual-energy operation starts next spring. Increased flexibility in the use of the polarized beams will be provided when installation of spin-rotation equipment in the switchyard is completed this winter.

The high-intensity H^+ beam (500 μA average current ≡ 400 kW beam power) must be very accurately controlled in position and size to avoid damage to targets, beam pipes or windows; this control requires accurate measurement of beam properties and continued monitoring of beam transmission. The target cells are difficult engineering problems. The level of induced activity is so high that they can only be serviced with remote handling techniques. The heat load from the targets is significant and all components in the vicinity of the targets or beam stop are subject to high levels of radiation damage. Progress to higher current will be paced by the ability of the experimental area to accept increased beam power.

Future Development Work

The preceeding paragraphs support the position that nearly all of the original expectations for the performance of LAMPF have been fulfilled. The major step yet to be made is that of routine production at the 1 mA level. This level of operation is nearly in hand from the accelerator. Duty-factor tests in late August 1979 showed that 9% duty-factor operation is practical without major retrofitting. Recent beam tests at peak currents of 13 mA show satisfactory beam quality,so an average current from the accelerator of 1 mA is within reach. However, operation at 1 mA average current may well uncover major problems in the experimental area which thus far has seen a maximum average current of only 670 μA.

Other improvements in the facility are mainly in response to the requirements of the experimental program. In the spring of 1980, a time-sharing method of providing a lower energy H^- beam will be

TABLE I

Tube Type	Function	Total Operating Experience (Mh)	Mean Life (kh)
7835*	Triode rf amplifier	0.14	12
4CW250,000	Series modulator	0.27	10
LPT-44**	Switch tube	1.7	19
VA862A	Klystron rf amplifier	1.4	50
L-5120	Klystron rf amplifier	0.3	12

*At the time of writing, LAMPF had on line two 7835 tubes that had been in use 30 kh.

**These high-voltage switch tubes require reprocessing every 2 to 3 kh.

in operation. This will provide an H^- beam of energy, as needed, between 400 and 800 while an H^+ beam of 800 MeV is produced. A more sophisticated method of dual-energy operation has been explored and is reported in a separate paper at this conference.[10]

Similarly, there is a strong demand for higher intensity polarized beams. The present source should be operating in late 1980 at the 30 nA level using known technology. If the atomic beam sources prove practical,one of these devices will be installed in a few years.

Further in the future, a 100 μA average-current proton storage ring[11] is to be filled from LAMPF. This will use a high-intensity H^- beam that will necessitate major changes in the H^- injector and transport, the transition region, and the switchyard. Changes in the transition region will be made first since they will upgrade the present dual-beam operation significantly.

Acknowledgement

The LAMPF project was first discussed some 17 years ago; a proper acknowledgement of the contributions made by a large number of people is beyond the scope of this report. Lew Agnew, Andrew Browman, Joe Bergstein, Ralph Stevens, Jr., Bob Cady, Lois Rayburn, and George Tubb were very helpful in preparing this paper.

References

1 D.C. Hagerman, "Meson Factories - 1977," IEEE Trans. Nuc. Sci., Vol. NS-24, No. 3, June 1977, pp. 1605-1610.

2 E.G. Michaelis, "Review of Meson Factories," IEEE Trans. Nuc. Sci., Vol. NS-23, No. 3, June 1975, pp. 1385-1396.

3 D.C. Hagerman, "The Status of LAMPF," Proc. 1976 Linear Accelerator Conf., AECL-5677, Sept. 14-17, 1976, pp. 12-19.

4 R.R. Stevens, Jr., J.R. McConnell, E.P. Chamberlin, R.W. Hamm, and R.L. York, "Injector Operations at LAMPF," Proc. this Conference.

5 E.A. Knapp, "High-Energy Structures" in Linear Accelerators, P.M. Lapastolle and A.L. Septier, Eds. (North-Holland Publishing Co., Amsterdam, 1970) pp. 601-616.

6 O.R. Sander, G.N. Minerbo, R.A. Jameson, and D.D. Chamberlin, "Tomography in Two and Four Dimensions," Proc. this Conference.

7 E.W. Hoffman et al., "High Intensity Beam Profile Measurements for the LAMPF Primary Beam Lines," IEEE Trans. Nuc. Sci., Vol. NS-26, No. 3, June 1979, pp. 3420-3422.

8 A.R. Swanson and R.E. Hill, "LAMPF First-Fault Identifier for Fast Transient Faults," Proc. this Conference.

9 LAMPF Users Handbook (November 1974).

10 G.R. Swain and D.C. Hagerman, "Simultaneous Beam of Different Energy from LAMPF," Proc. this Conference.

11 R.K. Cooper and G.P. Lawrence, "The Design of the WNR Proton Storage Ring Lattice," IEEE Trans. on Nuc. Sci., Vol. NS-24, No. 3, June 1977, pp. 1037-1039.