OPERATIONAL EXPERIENCE WITH THE FERMILAB LINAC

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Abstract

The Fermilab 200-MeV Linac has been in operation for nearly 22 years as a proton injector to the Booster synchrotron. It presently accelerates H^- ions to 200 MeV for charge-exchange injection into the Booster and to 66 MeV for the production of neutrons at the Neutron Therapy Facility. The beam intensity is typically 35 mA with pulse widths of 30 μsec for the Booster for high energy physics and 57 μsec for NTF at a maximum of 15 pulses per sec. During a typical physics run of nine to twelve months, beam is available for greater than 98% of the scheduled time. The Linac history, operation, tuning, stability and reliability will be discussed.

Introduction

The Fermilab 200-MeV linear accelerator began construction in May, 1968 [1,2] and achieved full beam on November 30, 1970 [3]. It has operated since as an injector to the 8-GeV Booster synchrotron and from September, 1976 for the Neutron (cancer) Therapy Facility providing 66-MeV protons for neutron production [4]. The early Linac accelerated protons for injection into the Booster. Initially it was planned to inject four turns of 75 to 100 mA to fill the Booster but later a single turn (2.8 μsec) of 300 mA proved more effective although straining the Linac to its limits [5]. In March, 1978 H^- ions were accelerated in the Linac and multiturn charge-exchange injection into the Booster became standard operation [6]. For short periods the Linac provided a low-intensity 200-MeV beam for proton radiography and electron-proton cooling studies.

Presently the Linac accelerates 35 mA of H^- ions which can be time shared for injection into the Booster and for Neutron Therapy. For the Booster a pulse of 10 to 20 μsec every few seconds is sufficient while NTF uses a pulse of 57 μsec at a 15-Hz rate for several minutes when treating patients.

Preaccelerator

The preaccelerator is a commercial 750-kV Cockcroft-Walton generator with a seven gap dc accelerating column and an ion source. The original source was a duoplasmatron which at one time provided 500 mA of protons to the Linac. Since 1977 there have been two 750-keV preaccelerators providing ~50 mA of H^- ions from a magnetron surface-plasma ion source [7].

A normal H^- ion source has a lifetime of 4-5 months. Some fail catastrophically but most operate smoothly with some adjustment the full time with a slow decrease in beam intensity (10-20%) during the last month. During the 1991 run, the source was reduced by 10% by lowering the arc current. This source ran for seven months with less decrease toward the end. Two preaccelerators provide the redundancy for rapidly switching to another source and for easier source maintenance [8].

The high voltage systems have operated well. The accelerating columns have only been cleaned and repolished a few times during their 15-20 year lifetime while the generator and its electronics have been very reliable especially after converting to solid-state electronics.

Low Energy Transport

The beam is transported from the original preaccelerator to the Linac through a straight four-meter line of three quadrupole triplets and one single-gap buncher. The line from the other preaccelerator is ten-meters long, has seven additional quadrupoles and two horizontal dipoles [9]. The lines merge before the second quadrupole of the first line using the second dipole. Each line contains an electrostatic chopper to determine pulse length for different uses. These lines have transmission of 98-95% with a growth in emittance of ~2 from beginning to end. The injector gives a 50-mA H^- "bunched" beam to the Linac with a 90% normalized emittance of approximately: $\varepsilon_{n(90)} = 2.1$-$2.3\ \pi$ mm-mr.

Linac

The Linac is a typical Alvarez drift-tube linac operating at 201.25 MHz [2]. It was designed to accelerate 75-100 mA of protons for four-turn stacking injection into the Booster with a beam pulse width of ~30 μsec. This pulse width allows some time for rf feedback control before chopping beam to the Booster. The Linac can produce beam at a 15-Hz rate commensurate with the cycle time of the Booster. Multiturn stacking and adiabatic capture into the Booster were not very efficient. To improve the beam quality a debuncher was installed in the 200-MeV transport line to decrease the momentum spread and to stabilize the mean momentum of the beam from the Linac. With the debuncher it is possible to operate the Linac at much higher beam intensities than designed and still be acceptable to the Booster. Given this option the Linac began operating with 500 mA of injected beam and 300 mA

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accelerated beyond Tank 1 and through the Linac. This permitted the Booster to achieve high intensity and efficiency with single-turn injection. For some time this was standard operation. Since one turn for the Booster is 2.8 μsec, the Linac pulse was 5 μsec. It was necessary to use manually adjusted feed-forward circuits to the rf systems to anticipate beam. This put considerable strain on the Linac rf systems, operation and maintenance [10].

In 1978 H^- ions of moderate (~50 mA) intensity were injected into the Linac and subsequently accelerated (35 mA) to full energy [9]. Within a month the Booster achieved record intensity using multiturn H^- charge-exchange injection. Since that time this has been the standard operating mode for Booster injection. It has unquestionably proved to be the most efficient, effortless and reliable of the methods tried for the Linac and Booster [6].

The Linac requires minimal tuning or attention. The drift-tube quadrupoles, and the rf amplitude and phase are virtually never changed. Good conditions are achieved by tuning the low energy line and a few steering magnets. Performance of the Linac is checked daily or as necessary by observing beam profiles in the 200-MeV output line. Upon start-up or when needed, about every few weeks, the Linac tuning is investigated. With proper tuning the capture efficiency of Tank 1 is 72%. Beyond Tank 1, all of the beam is accelerated to 200 MeV.

NTF

The Neutron Therapy Facility began cancer patient treatment in September, 1976 [4]. During treatment, NTF uses the maximum beam the Linac can provide: 35 mA, by 57 μsec pulse width, at 15 Hz for several minutes per an irradiation field. A dipole between Linac Tanks four and five sweeps the beam out of the Linac toward a beryllium target where neutrons are produced. The dipole may be energized for patient treatment only when a timing signal from the Main Control Room indicates that beam is not needed for high energy physics. Thus, while a patient is being treated the therapy beam can be interrupted for about half a second to send a pulse to the Booster. The patient is not aware that this is happening. In its most demanding mode the high energy physics program requires one pulse of beam once every 2.4 seconds.

NTF uses the linac beam to treat patients three days per week. On those days the beam is available as long as is necessary to treat all the patients, generally from six to nine hours each day. On rare occasions treatments have been delayed due to minor linac problems, but scheduled treatments have never been cancelled due to linac downtime.

Reliability and Downtime

The Linac operates with a reliability of 98% during physics runs. Table 1 shows the total downtime for eight runs, from 1983 to the current collider run. Averaged over a run the downtime is typically 2% or less.

TABLE 1. Downtime Percentage of Total Hours.

Run		Downtime
10/83	7/84	2.25 %
8/86	5/87	1.68 %
6/87	2/88	1.28 %
6/88	6/89	1.36 %
2/90	8/90	1.94 %
12/90	2/91	1.42 %
6/91	2/92	1.87 %
4/92	7/92	2.34 %
Average		1.76 %

The monthly statistics have variations from <0.4% when all runs well to 4.5% when major items fail or become erratic. Over half of the downtime entries are three minutes or less, predominantly caused by arcs in the rf modulators, power amplifiers or the preaccelerator high voltage. They represent however only 7.3% of the actual downtime. Occurrences over fifteen minutes account for 71% of the downtime. Usual problems here range from replacing tubes to vacuum leaks.

Fermilab no longer has regularly scheduled maintenance periods during a run. Preventative maintenance is done on an "annual" basis between HEP runs. Necessary maintenance is done during a failure in some part of the accelerator. The system with the failure is charged the downtime while other systems conduct necessary maintenance while time permits. If one cannot keep a necessary component running until such an opportunity arises then a shutdown is requested and downtime is charged. Downtime due to power outages, once or twice per year, is not included as it is not considered an accelerator failure. Following a power outage the Linac can be operational within a few hours.

Table 2 shows the percentage of the total downtime caused by the major Linac systems.

TABLE 2. Linac Downtime by Major System.

System	Downtime
Modulator	32.5 %
Driver	12.9 %
Power Amplifier	11.6 %
RF Miscellaneous	8.6 %
RF Unknown	5.7 %
Preaccelerator	13.7 %
Vacuum Systems	4.2 %
Water Systems	4.6 %
Quadrupole P. S.	3.1 %
Linac Miscellaneous	3.0 %

RF Miscellaneous includes problems with RF phasing, the RF transmission lines, modulator charging systems, etc. Linac Miscellaneous includes problems from the 200-MeV area, trim magnets, roof leaks, etc.

The largest downtime comes from the RF

modulators. They have accumulated 32.5% of the total downtime. In 1984 a major modification to the modulators was made by replacing the first stage tube with a MOSFET and improving the feedback loops [11]. Not only did this improve the modulator reliability by 15%, but we have since had only one cavity rf-vacuum window failure.

New Controls

In February, 1992 the third control system in the history of the Linac was installed [12]. The new Control System consists of nine VME crates which control seventeen sub-systems in the Linac and communicate over a token ring network to Macintosh consoles in the Linac Gallery and to μVax consoles in the Main Control Room. As in the previous systems, this system has the following features: To monitor the Linac and allow data acquisition and control at the 15-Hz operating rate of the Linac; to immediately inhibit further beam pulses if a critical device goes beyond a preset tolerance; to give a display of devices out of tolerance; to allow local control of all parameters; and to be modular with the arrangement of the Linac.

The VME local control stations each function as a full control system. They consist of a MC68020 cpu contained in a MVME 133A-20 cpu card, a token ring adapter, a 1 MB non-volatile (battery-backed) RAM, an Arcnet adapter and a 4-channel 2-MHz digitizer. Each VME station interfaces to the hardware via the Arcnet local area network to several Smart Rack Monitors (SRM) [13]. The SRMs provide all of the local data gathering and control. They have the versatility to be configured as A/D, D/A, digital I/O, binary interface, or timers; or in combinations. Each station contains software feedback loops to regulate the rf amplitude and phase during beam pulses. The amplitude is regulated to 0.7% and intertank phase to ~1%.

Upgrade

The Linac has been a very successful accelerator and can provide more beam than can be accepted by the Booster. To increase the intensity in further accelerators requires higher energy from the Linac. Early next year (1993) the Linac will undergo a major conversion to 400 MeV. This Upgrade, which is essentially fully constructed, will be accomplished by removing the last four of the nine drift-tube tanks and replacing them with a series of side-coupled cavities having approximately three times higher accelerating field. Five 201.25-MHz drift-tube cavities will remain to accelerate the beam to 116.5 MeV. At this point the beam will go through a transition section to give a longitudinal rotation and into the 805-MHz side-coupled accelerator which will accelerate the beam to 401.5 MeV [14,15].

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