OPERATION AND IMPROVEMENTS OF THE FERMILAB 400 MEV LINAC

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Abstract

The 400 MeV Fermilab Linac Upgrade commissioning began August 28, 1993. High energy physics collider operation (run 1b) began in November 1993 and ended March 1, 1996. The Linac, operating at 98% reliability, provided 400 MeV H^- beam to the Booster and 66 MeV H^- beam to the Neutron Therapy Facility. During this time, the beam intensity, which initially was administratively set to 35 mA, rose to a peak of 50 mA while losses decreased significantly. This paper discusses the Linac operation and reliability since the Upgrade.

Introduction

Commissioning of the high energy part of the Linac started August 28, 1993. Prior to this the entire system was installed in the Linac tunnel, along side the drift tube cavities and operated without beam for one year. The last four cavities (116 to 200 MeV) of the original Linac were removed three months before commissioning, and the new side-coupled structure (116 to 400 MeV) was moved into place and reconnected.

When commissioning begun low intensity coasting beam was achieved in about eight hours. Once the low energy linac was properly matched, beam coasted through the high energy linac with little loss. Good transmission required empirical tuning of the high energy trim magnets and quadrupoles.

Tuning of the accelerating gradients and phases began immediately, starting with the first of seven side-coupled modules and the longitudinal matching sections. The new high energy structure is composed of two small longitudinal matching sections to match from 201.25 MHz into the new 805 MHz system followed by seven side-coupled accelerating modules. Each accelerating module is composed of four cavities with each cavity having 16 cells. A 12 MW klystron feeds each module [1]. The RF amplitude and phase to each module was determined by a process called phase scan signature matching [2] where the phase difference between two beam detectors is measured as the RF phase of the module is scanned through 360 degrees and compared to the calculated curve. Beam measurements and RF studies required seven days and the first low intensity 400 MeV beam was accelerated on September 4, 1993 [3].

Shielding assessment studies, to verify the radiation integrity of the Linac enclosure, were required and done before increasing the intensity. Commissioning of the Booster 400 MeV line, injection and Booster acceleration proceeded in concert until the Main Ring and Tevatron began operations.

Steady improvement in the beam intensity, losses and stability were made during this time. At the time of Main Ring startup, early October 1993, the Linac was providing the design intensity of 35 mA with >98% transmission through the high energy linac.

While commissioning, the Fermilab Linac Department was augmented by several people from the Superconducting Super Collider Linac Group, the Institute for Nuclear Physics, Moscow, and the Institute of High Energy Physics, Beijing.

During 1994 the linac group worked to increase intensity and lower losses. Much of this involved adjustment of the ion source parameters to operate at 65 mA and above [4]. On the high energy linac, studies continued to refine the longitudinal and transverse tunes. This represented small changes to RF phases and amplitudes of the system, adjustment of individual quadrupoles, and much tuning of the high energy trim magnets. All combined, the Linac output intensity increased from 35 mA to 44 mA.

During the February 1995 shutdown the low energy buncher RF system was upgraded and the cavity began operating at 30% higher gradient. This resulted in higher capture (72%) into the low energy linac and the intensity improved to 48 mA. This also appeared to help the high energy linac transmission with a resulting increase in the Linac output to 47 mA.

Operation

Chart 1 shows the monthly average intensity at 400 MeV through the period of the Collider Physics run. The general trend is up with dips caused by ion source aging and differences in the two ion sources. Ion source improvements were implemented in September 1994 and gave a significant increase in intensity. The smaller increase from March 1995 is a result of the work on the low energy buncher. These are monthly averages not peak intensities. During the period of March 1995 to the end of the run it was not uncommon to operate for days at 47 to 48 mA and a record of 50 mA for H^- ions was achieved during studies at the end of the run.

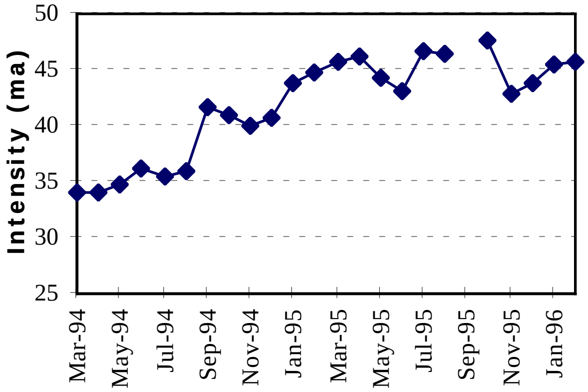

Chart 1, Average intensity.

Beam losses in the high energy linac are measured by loss monitors of the style used in the Main Ring and Tevatron

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* Operated by the Universities Research Association under contract with the U.S. Department of Energy.

[5]. They are not calibrated in any units but are used as a comparison with previous running. Tuning of the high energy trim magnets is typically done by looking at the loss monitors and tuning for the lowest losses. Chart 2 displays the average monthly normalized losses during Collider Run 1b.

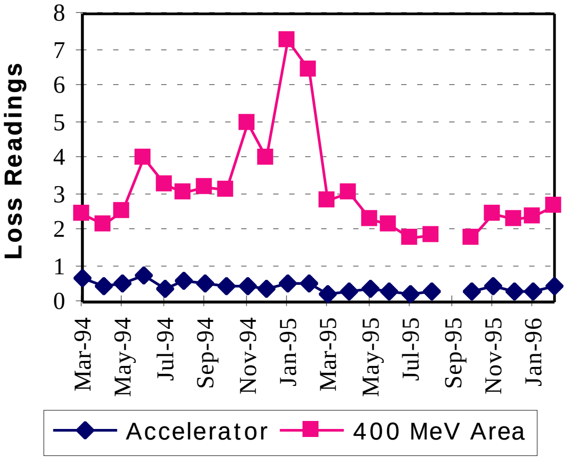


Chart 2, Average Losses.

Normalized losses in the accelerating section of the high-energy linac changed very little as the intensity rose. Losses would rise briefly until the best tune was found for that intensity and often decreased to a level lower than the starting point. The 750 keV line tuning has a large effect on the high energy linac losses. A different trim setting is needed for each ion source. Settings have been found which allow both ion sources to provide equivalent beam intensities and losses.

A major improvement in the losses occurred in February 1995. Studies which culminated in a new high energy linac quadrupole tune reduced the losses everywhere in the high energy linac by a factor of two. As the source current increased new quadrupole settings were necessary in the high energy linac. New setting were found using TRACE3D and beam profiles measured at three locations in the transition section and at nine locations along the side coupled structure. Beam profile measurements at the transition section, with TRACE3D analysis, provided Twiss parameters of the beam from the low energy linac. This provided new transition quadrupole settings which produced a waist at the entrance to the high energy linac. After new settings for the transition section were installed, tuning of the trim magnets was done to minimize losses through the high energy linac. At this point an attempt was made to set the rest of the quadrupoles for a FODO structure however the losses with these setting were to high at the ends of modules 2 and 3 so less radical quadrupole settings for modules 1 and 2 were tried. These settings, as 'suggested' by TRACE3D, had the smallest beam size in modules 2 and 3 with clean transmission through the rest of the linac. A best solution was found after several iterations. Chart 3 shows the decrease in the losses during the month of February when these studies were performed.

Chart 4 is a TRACE3D display for the final setting of the linac quadrupoles. The low beam losses in the Linac, good running conditions for the Booster and other operational requirements have forced us to accept these settings and give up on a FODO structure.

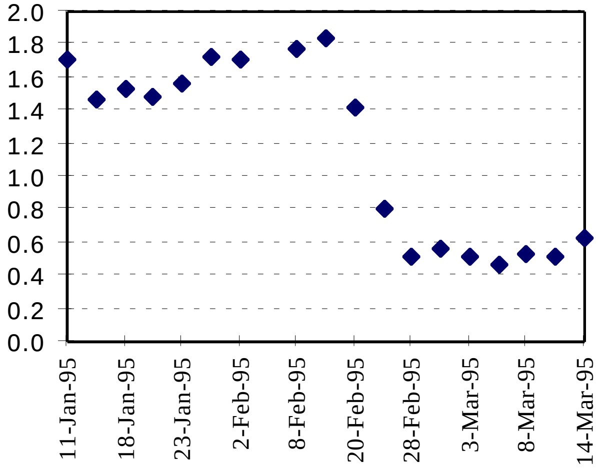
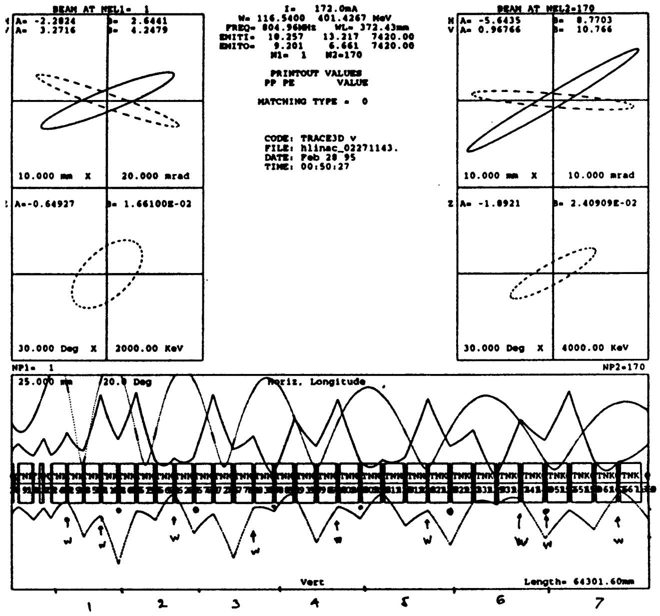


Chart 3, Losses during quadrupole retuning studies.



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W= 116.5400   401.4267 MeV
FREQ= 804.96MHz   WL= 372.43mm
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EMITO=   9.201    6.661  7420.00
     N1=  1    N2=170

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MATCHING TYPE =  0

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FILE: hlinac_02271143.
DATE: Feb 28 95
TIME: 00:50:27
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Chart 4, TRACE3D display for high energy linac quadrupole tune.

The 400 MeV area, because of a Lambertson magnet which has high end effect fields in the field free region, is much harder to tune and much less forgiving of changes in intensity and beam size. Losses in that area are typically a factor of six higher than in the accelerator and in the past the ratio has been as high as 13.5. The existing tune is a compromise between the needs of the 400 MeV dump area and the Booster injection line. The present tune gives the lowest losses in the dump line while not compromising the Booster operation.

Reliability

Reliability in the entire Linac was better than 98% before the Upgrade. In the first three months of 400 MeV operation reliability averaged 94.7%. Except for one klystron problem this increase was due to problems with the low energy linac. This is because people were to busy, during the shutdown, with installation of the Upgrade to do normal maintenance on the low energy systems. As the run progressed the reliability of the Linac as a whole returned to the 98% level with the majority of problems requiring less than five minutes to correct. After the first three months of running the linac downtime was much less than 2% except for a failure every three to four months requiring several hours to repair.

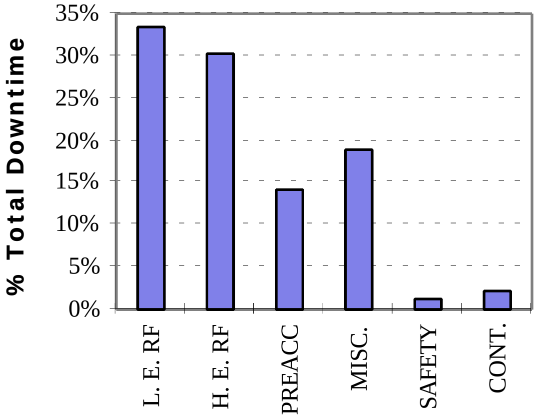

Chart 5, Percent of the total Linac downtime caused by each major system.

The 805 MHz, 12 MW klystrons, a major part of the Upgrade system, has operated extremely well. Of the 7 large and 3 small (200 kW) klystrons, none has yet to fail and many are approaching 30,000 hours operation.

Keeping in mind that the total linac downtime is about two percent, the major reliability problems are the RF modulators in both the high energy and low energy linacs (Chart 5). Subsystems with smaller but significant downtime are: the preaccelerator high voltage supplies, the low energy RF power amplifiers, the low energy cavities, and the high energy low-level RF components.

The low energy linac modulator problems are almost exclusively due to the tubes in use. The tubes are old designs and many are no longer made by the original manufacturer. Of the fifteen switchtubes to control the power tube high voltage, three per a RF station, 28 were replaced over this two year period. These tubes typically fail in one of two modes: voltage breakdown and instabilities. They are used as a linear amplifier and the current manufacturers have trouble making tubes that work in this mode. This requires working with the manufacturers to produce tubes that meet our application.

The high energy linac modulator problems are more varied but a majority of the failures concern the HV SCR switches for the charging supplies and pulse forming networks. Several of these switch banks have been replaced and work continues to improve their reliability. Other problems include the SCR firing circuits and high voltage cable breakdowns.

Current Performance

The Linac is now running at intensities between 45 and 48 mA. The ion source provides approximately 65 mA of H^- beam through the 750 keV line and to the entrance of the Linac. Of this 70-72% is captured in tank 1 and accelerated through the low energy linac to 116 MeV (tank 5). Transmission through the high energy linac is greater than 98% with usually less than 1 mA lost between the output of the drift tube linac tank 5 and the output of the coupled cavity structure (400 MeV). Most of this loss is in the 805 MHz coupled cavity modules 1 and 2 due to the inability to longitudinally capture all of the beam from the 201.25 MHz drift tube linac.

References

[1] C. W. Schmidt, "The Fermilab 400 MeV Linac Upgrade". Proc. 1993 Part. Acc. Conf., May, 1993, Washington D.C., IEEE Cat. No. 93CH3279-7, p1655.

[2] T. L. Owens, et.al., "Phase Scan Signature Matching for Linac Tuning". Linac94 Proceedings, August 1994, Tsukuba, Japan, p893.

[3] E. S. McCrory, "The Commissioning and Operation of the Fermilab 400 MeV Linac". Linac94 Proceedings, August 1994, Tsukuba, Japan, p36.

[4] M. Popovic, et.al., "Fermilab Linac Injector, Revisited". 1995 Part. Acc. Conf., May 1995, Dallas, TX, IEEE Cat. No. 95CH35843, (WPA06), p917.

[5] M. Johnson, "Loss Monitors". AIP Conference Proceedings 212, Accelerator Instrumentation, 1989, p156.