Commissioning and First Operational Experience of the 400 MeV Linac at Fermilab

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Abstract

Commissioning of the Fermilab High Energy Linac during September and October of 1993 has increased the energy of the H- linac from 200 to 400 MeV. The Linac Upgrade is one portion of the Fermilab Upgrade and is intended to reduce the incoherent space-charge tuneshift at injection into the 8 GeV Booster. To accomplish this increase in energy within the existing enclosure, four 201.25 MHz drift-tube linac tanks have been replaced by seven 805 MHz side-coupled cavity modules to accelerate the beam from 116 MeV to 400 MeV. Each module is driven with a klystron amplifier delivering 10 MW of peak power for 60 μsec with a maximum pulse repetition rate of 15 Hz. Nominal beam current is 35 mA with a pulselength of 40 μsec. Results from commissioning and operational experience during Fermilab Collider Run 1B are presented.

1. INTRODUCTION

The Fermilab linear accelerator has been in operation for nearly 24 years as an injector to the Booster synchrotron [1]. The recent upgrade [2] of this accelerator has involved the replacement of four drift-tube linac tanks with seven side-coupled cavity modules to increase the output energy of the Linac from 200 MeV to 400 MeV. The layout of the Fermilab Linac is shown schematically in Figure 1.

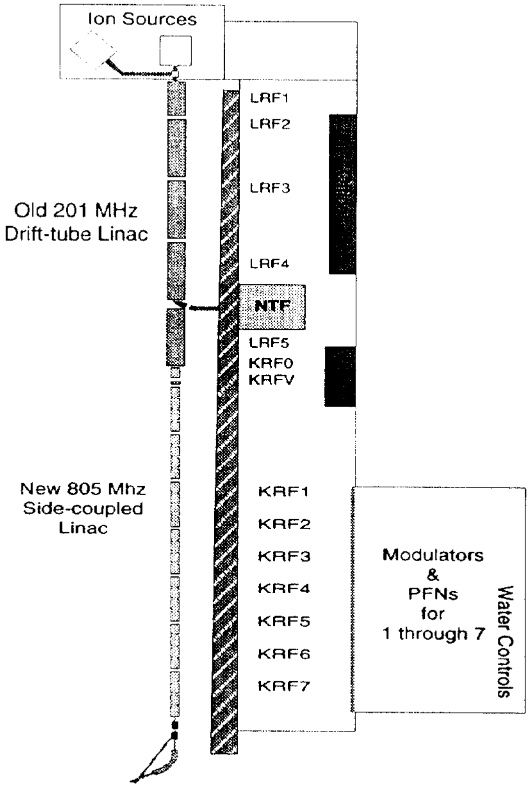

Figure 1. Schematic Diagram of FNAL Linac.

1.1 Preaccelerator

The preaccelerator area consists of two 750 KeV Cockcroft-Walton accelerators each of which contains a magnetron surface-plasma ion source [3]. Each source typically produces 50 mA of H- ions. The presence of two preaccelerators provides redundancy for source maintenance.

1.2 Drift Tube Linac (DTL)

The Drift Tube Linac (DTL) is a typical Alvarez drift-tube linac operating at 201.25 MHz. With the use of a single-gap buncher cavity preceding the DTL, 35 mA or 70% of the preaccelerator beam is captured in the first tank and accelerated out of tank 5 at an energy of 116 MeV.

1.3 Transition Section

The 3.6 meter long transition section provides both longitudinal and transverse matching between the DTL and the new side-coupled modules. Transverse matching is accomplished through four quadrupoles located within the transition section. Longitudinal matching is effected by a 16 cell 805 MHz buncher located near the end of DTL tank 5 and a 4 cell vernier buncher located near the entrance to side-coupled module 1.

1.4 High Energy Linac (HEL)

Acceleration to 401 MeV is accomplished by the 7 Side-Coupled Modules of the HEL which operate at an rf frequency of 805 MHz. The use of a higher frequency allows high accelerating gradients so that the increase in output energy of the Linac can be achieved within the same tunnel enclosure. The side-coupled cavities operate at a maximum surface gradient of 36 MV/m which is 1.35 times the Kilpatrick level. The average accelerating gradient is 8 MV/m. The 12 MW of RF power required for each of the seven modules is provided by Litton klystrons designed for this project. The Low Level RF system is implemented in VXI and maintains feedback on the cavity phase and amplitude to 0.5° and 0.1% respectively. An adaptive Feed Forward system removes beam loading transient affects. A summary of the general parameters of the HEL is given in Table 1 [4].

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[*] Operated by the Universities Research Association under contract with the United States Department of Energy.

1.5 Diagnostics

A full complement of diagnostics are available in the HEL. Beam position monitors are located at the bore of most quadrupole magnets. Dipole trim magnets provide the ability to correct steering. Wire scanners in conjunction with tuning of quadrupole gradient yield a determination of the beam emittance and Twiss parameters. Resistive Wall Current Monitors and Radiation Loss Monitors determine the beam current transmission. Bunch length detectors [5] provide a measurement of the phase length of the beam.

2. COMMISSIONING

Commissioning of the HEL began August 29, 1993 and was completed in October 1993. Full intensity and energy were achieved with the first month of beam commissioning. Typical beam parameters are given in Table 2. Commissioning of the HEL involved contributions from many personnel at Fermilab. Additional assistance was provided by personnel from the Institute for Nuclear Research (Troitsk, Russia), the Institute of High Energy Physics (Beijing, China), and the SSCL (Texas).

Table 1
Linac Upgrade Parameters

Initial Kinetic Energy	116.5 MeV
Final Kinetic Energy	401.5 MeV
Length	63.678 m
RF Frequency	805 MHz
Beam current	35 mA
Beam pulse length	40 µsec
Repetition rate	15 Hz
Accelerating phase	-32 degrees
Average axial field	8.1-7.1 MV/m
Maximum surface field	36.8 MV/m
Kilpatrick limit	26 MV/m
Number of modules	7
RF power per module	12 MW
Number of sections per module	4
Number of rf cells per section	16
Klystron Voltage	170 KV
Klystron Current	141 A
Transverse lattice	FODO
Transverse Phase Advance	79 degrees
Quadrupole magnetic length	8 cm
Quadrupole bore radius	2 cm
Quadrupole poletip field	4.6 kG
Quadrupole gradient	263 KG/m
Cavity bore radius	1.5 cm

Table 2
Typical Beam Parameters

Transverse Emittance		
(90% normalized πmmmrad)	116 MeV	400 MeV
horizontal:	6.7	5.9
vertical:	4.9	8.0
Longitudinal Emittance	1.1 x 10^{-4} eV sec	
Transmission	98%	

2.1 Longitudinal Phase-Scan Match

The Phase-Scan Match algorithm is a relatively simple method for longitudinal linac tuning [6]. The module rf phase is scanned over a full 360 degree range while the phase of beam signals from stripline detectors (Beam Position Monitors) is measured. Reference phase is taken from the master oscillator for the linac. Theoretical curves of beam phase versus module phase are matched to the measured curves to determine the module accelerating field amplitude and phase. Figure 2 shows an example of the phase-scan procedure. For this module the algorithm determines that the accelerating gradient is 4% larger than the design value. Time-of-Flight measurements and the classical Delta-T technique provide additional checks in the process of longitudinal tuning.

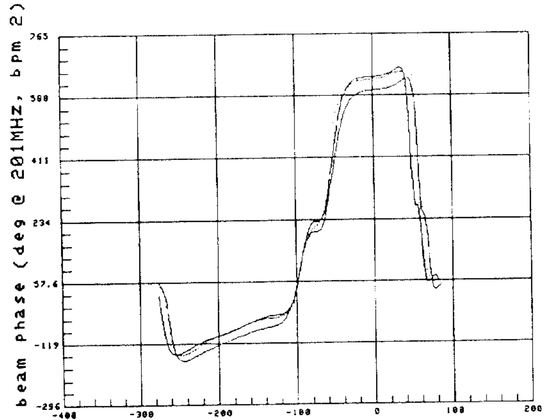

Figure 2. Upper curve is fit to data points. Lower curve is the target curve for this module.

2.2 Transition Section Transverse Matching

Wire Scanner profiles in the Transition Section allow the determination of Twiss parameters at the exit of the DTL. Computational modeling using TRACE-3D or FLAT (INR-Troitsk) determines quadrupole settings for a proper transverse match into the lattice of the HEL.

2.3 Beam Steering

The HEL has a significantly reduced physical aperture than that found in the DTL. In addition, the lattice of the side-coupled structure provides significantly less transverse focusing than the DTL. In the early portion of the HEL the beam occupies over 95% of the available physical aperture (3.0 cm). In order to prevent beam loss and the creation of excess radiation, the ability to correct beam position throughout the HEL is of importance. A commonly used orbit smoothing algorithm [7] in the correction of closed orbits of circular machines has been implemented to achieve a global least-squares minimization of beam position errors in the HEL [8]. Figure 3 shows the improvement achieved by this algorithm over a wide range of operational conditions.

3. OPERATIONS

The Fermilab Linac has a long history of reliable operation [9]. The installation of the HEL has not adversely affected machine performance. Since the start of Fermilab's Collider Run 1B in November 1993, the Linac has been operational 97.2% of the total scheduled hours. This 2.8% downtime is distributed as follows: 0.6% Preaccelerator; 1.1% DTL; 1.0% HEL; and 0.1% Miscellaneous.

Although the Linac is capable of a 15 Hz repetition rate the major usage of Linac beam is for production of antiprotons as a part of Fermilab's High Energy Physics program. The cycle time of this process is 0.5 Hz. With such high accelerating gradients in the side-coupled structures cavity sparking was of concern. The sparking rate since the beginning of Collider Run 1B is 0.037% which is well below the design value of 0.1%. This translates into a loss of only 10 beam pulses per day.

The goal of increased performance for the Fermilab Booster has also begun to be realized [10]. Currently the Booster is capable of routinely delivering 3.2 x 10^{12} protons at an energy of 8 GeV with a transverse emittance of 15 π mm mrad (95% normalized). The Fermilab Main Ring has also achieved a record 2.7 x 10^{12} protons at 120 GeV delivered to the antiproton target.

4. REFERENCES

[1] C.D. Curtis, et al. "Operating Experience with the NAL 200-MeV Linac", Proceedings of the 1972 Proton Linear Accelerator Conference, Los Alamos, USA, p. 17.

[2] R.J. Noble, "The 400 MeV Linac Upgrade at Fermilab", Proceedings of the 1992 Linear Accelerator Conference, Ottawa, Canada, p. 565-569.

[3] C.W. Schmidt and C.D. Curtis, "Operation of the Fermilab H- Magnetron Source", Proc. 4th Int. Symposium on the Production and Neutralization of Negative Ions and Beams, Brookhaven, US, Oct. 1986, AIP Conf. Proc. No. 158, p. 425.

[4] "Fermilab Linac Upgrade Conceptual Design Report", November 1989.

[5] E.S. McCrory, et al. "Use of an INR-Style Bunch-Length Detector in the Fermilab Linac", Proceedings of the 1992 Linear Accelerator Conference, Ottawa, Canada, p. 662-664.

[6] T.L. Owens and M.B. Popovic, "Phase Scan Signature Matching for Linac Tuning", Fermilab Report LU-186, November 1992.

[7] R. Talman, "A Universal Algorithm for Accelerator Correction", AIP Conference Proceedings 255, A. Chao ed., AIP, (1992) 66.

[8] K. L. Junck, "Beam Steering in the Fermilab Linac Upgrade", Fermilab Report LU-211, May 1993.

[9] L. Allen, "Operational Experience with the Fermilab Linac", Proceedings of the 1992 Linear Accelerator Conference, Ottawa, Canada, p. 82-84.

[10] D. McGinnis, "Status of Fermilab Booster After the 400 MeV Linac Upgrade", Proceedings of 1994 EPAC, London, England.

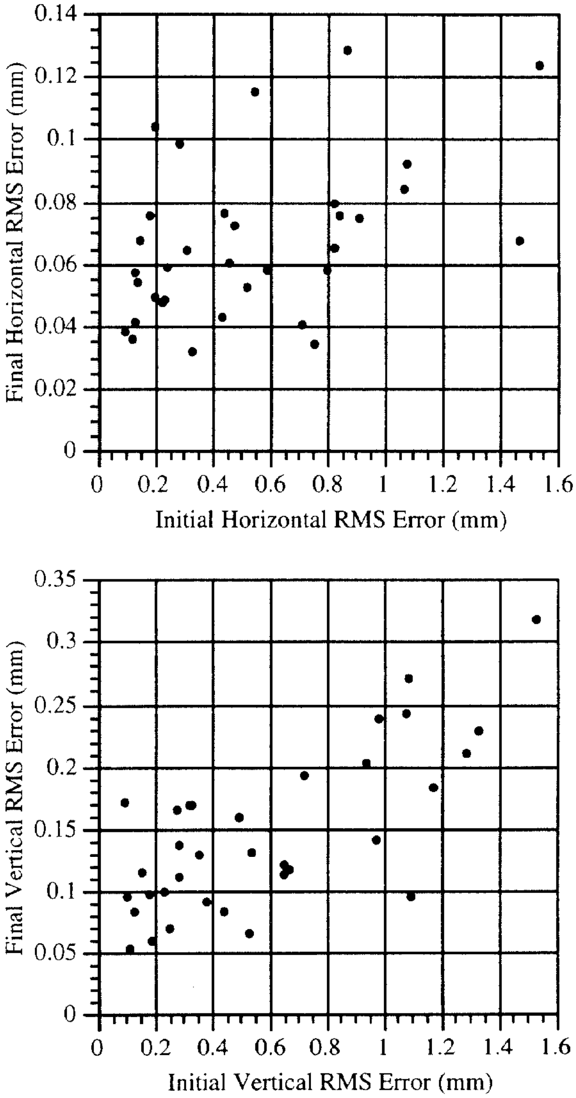

Figure #3. Results of Beam steering algorithm over a wide range of operational conditions. Final RMS Beam Position Error throughout the entire HEL versus Initial RMS Beam Position Error is shown for both the horizontal and vertical planes.