THE COMMISSIONING AND INITIAL OPERATION OF THE FERMILAB 400 MEV LINAC*

Elliott S. McCrory
Fermi National Accelerator Laboratory*
Batavia, IL 60510, USA

ABSTRACT

The linear accelerator at Fermilab has been upgraded to produce a 400 MeV H^- ion beam at 35 mA. The last half of the old 204 MeV, 201 MHz drift-tube Linac was replaced with an 805-MHz side-coupled linac during the summer of 1993. Milestones of commissioning and outlines of the commissioning techniques are presented.

Beam commissioning began on 28 August 1993. Low current 400 MeV beam was obtained on 5 September and full current beam was achieved on 27 September. Collaborations with the INR in Moscow, the Institute of High Energy Physics, Beijing and with the SSCL in Texas were crucial to achieving this speedy schedule.

The operation of the Linac has been good. Statistics are presented for: downtime, sparking rate, losses and component aging. The performance of the following systems is also presented: 12 MW klystron, modulator, cavity water, cavity vacuum, diagnostics and controls. The impact of this upgrade on the rest of the Fermilab Collider is discussed.

INTRODUCTION

The Fermilab 400 MeV Linac (the Linac, Figure 1) accelerates H^- ions from 750 keV to 401 MeV through 79 m of 25-year-old 201 MHz drift-tube linac to 116 MeV, through a new 4 m 201/805 MHz transition section and, finally, through 60 m of 805 MHz side-coupled structure (SCS) linac to 401 MeV. Beam is chopped at the end of the Linac and extracted through a lambertson magnet, down a 50 m transfer line into the Booster synchrotron. Associated with the Linac are a 400 MeV diagnostics area for dumping and studying unneeded beams, beam focusing and beam diagnostics systems. The Linac is driven by 201.25 MHz, 5 MW, triode-based RF systems to 116 MeV, and by 805 MHz, 0.2 and 12 MW, klystron-based RF systems to 401 MeV. The 805 MHz part of the Linac, its installation, commissioning and operations are the focus here.

This paper is organized as follows. First, an overview of the components of the recently-installed 400 MeV Linac are given. Then, several chronological accounts are given: the pre-commissioning and the commissioning of the RF systems, the installation of the new SCS modules and finally the beam commissioning. Lastly, a summary of the present operation is given with emphasis on the observed reliability.

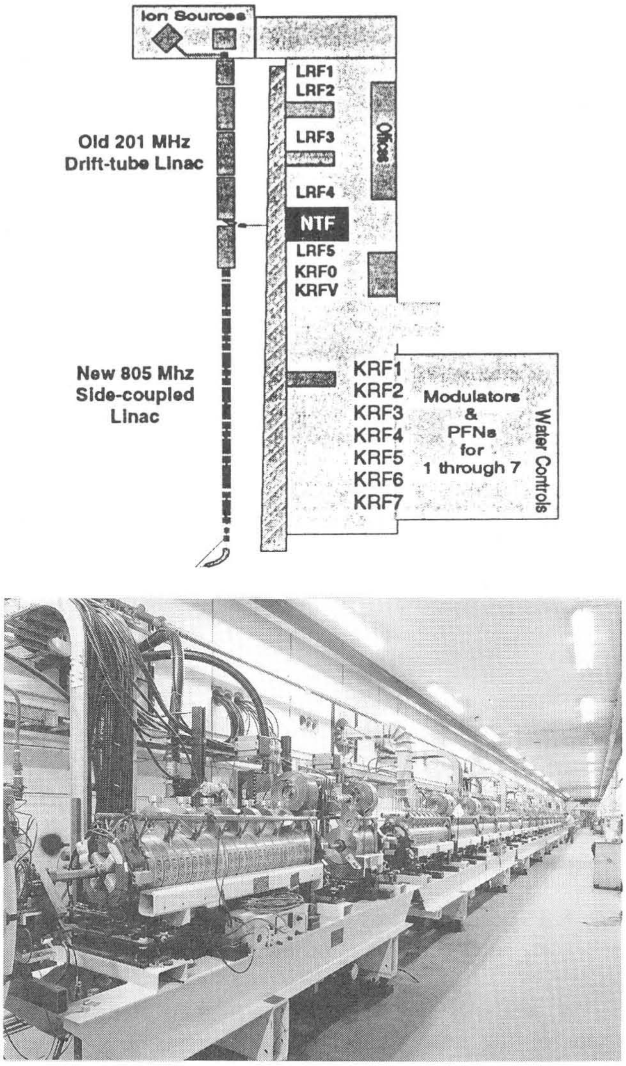

Figure 1, Top: Schematic of the Fermilab Linac; Bottom: Photo in the accelerator enclosure.

OVERVIEW OF THE LINAC

The major aspects of the Linac are: beam quality, RF, accelerating cavities, modulator, water, diagnostics, controls and safety. [1, 2]

The parameters of the beam produced by the Linac are summarized in Table 1. These are fairly standard for an H^- linear accelerator. The shortest pulse, 20 µsec, is used for Linac studies; the longer pulses are used for multi-turn injection into Booster. The longest time, 45 µsec, corresponds to 11 turns injected.

The RF system parameters are summarized in Table 2.

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Parameter	Value	Units
Beam Particle	H-minus	
Repetition Rate	15	Hz
Current	35	mA
Energy	401	MeV
Beam Power	14	KW
Momentum	956	MeV/c
Pulse Duration	20-45	µsec
Duty factor	0.03-0.07	%
Transverse Emittance	1	π-mm-mr, RMS
Longitudinal Emittance	5 E-5	eV-sec

Table 1., Beam Parameters for the Linac

The 805 MHz Linac is driven by a new klystron from Litton Industries, designed specifically for this project. The modularity and the flexibility of the system has been good. For example, the bandwidth of the feedback and the character of the feedforward system in the Low-level RF (LLRF) had to be changed during commissioning, with only minimal impact to the program.

The LLRF system resides in a VXI-bus crate and is controlled by two Fermilab-built modules. On one module is the feedback and feedforward systems for both the phase and the amplitude. These are regulated to ± 1° in phase and ± 1% in amplitude. The other VXI card contains a voltage-controlled crystal oscillator (VCXO) for driving the cavity when it is out of tune and a 360° electronic phase shifter to facilitate the phase-scan match measurement [3].

The 31 SCS RF sections are arranged as follows. The 28 sections which comprise the accelerating structures are 16-cells long, each section representing a single $\beta\lambda/2$ mechanical construction (e.g., 16 cells are all the same size). They are grouped by fours into modules, which are driven by a 12 MW klystron. There is a 16-cell buncher cavity just downstream of DTL Tank 5, a 4-cell vernier cavity between the buncher and the first accelerating module, and a 3-cell debuncher cavity 45 m downstream of the last accelerating module, about 20 m upstream of Booster injection. The last three sections mentioned here are powered by a 0.2 MW klystron from Varian, adapted for pulsed operation from their stock of TV broadcast klystrons.

The average accelerating gradient in the SCS is 7.5 MV/m. The peak surface field is 37 MV/m, which is 1.35 kilpatrick.

The cavities are designed without cooling in the nose-cones or in the web between cells. Therefore, the nose-cones normally run about 2 C hotter than the outer jacket. When a cavity has been off for more than a few minutes, it is necessary to drive the cavity at a frequency other than the nominal one in order to warm up the nose cones and bring it back into proper resonance.

Water cooling is required for the SCS sections, for the klystrons and for the waveguides. The temperature regulation of the cavities is critical [4]: the response of the cavities is -14.3 kHz/° C. A software control loop has been implemented in the local control station to provide the necessary temperature control for the cavities. The cooling for the waveguide is important because a section of each waveguide is partially exposed to the outside. At this time, there is no control on this system, only temperature readbacks. The cooling for the klystrons is only for heat removal. [5]

The 24 MW modulator system in the high-energy half of the Linac consists of a 20 kV charging supply, a 26-cell pulse-forming network and a 20:1 step-up transformer [6]. The voltage regulation on this system has been measured at 0.05%, which directly leads to a gradient error of 0.06% in the accelerator.

The focussing lattice chosen for the Linac is FODO, with a new design quadrupole [7]. A gradient of approximately 20 T-m/m in a 4 cm aperture is required. We have

201 MHz RF		
Number of systems	6	(1 low power)
Peak power	5	MW
Pulse Duration	180	microseconds
Duty Factor	0.375	%
Overall Gain	31	dB
Input Voltage	21	KV
Input Current	190	A
Stages of amplification	5	
Main power amplifier	triode, Burle model 7835	
Frequency Tuning	computer-controlled cavity slug	
Amplitude Regulation	Modulator voltage, feeback	
Phase regulation	LLRF feebback	
Long-term Ampl. Reg.	Software	
Long-term Phase Reg.	Software	
LLRF system	NIM Module	

805 MHz RF		
Number of Systems	10	(3 low-power)
Peak power	12	MW
Pulse Duration	70	microseconds
Duty factor	0.105	%
Gain	52	dB
Efficiency	48	%
Input Voltage	170	KV
Input Current	140	A
Stages of amplification	2	
Main power amplifier	klystron, Litton model L-5859	
Frequency tuning	VXCO in LLRF	
Amplitude Regulation	LLRF level, feedback & feedforward	
Phase regulation	LLRF feedback & feedforward	
Long-term Ampl. Reg.	Software	
Long-term Phase Reg.	Not needed	
LLRF system	VXI-based controller	

Table 2., Parameters of the two types of RF systems in the Fermilab 400 MeV Linac

chosen a constant gradient, so the phase advance per cell is about 74°. It is necessary to re-tune the quads if the beam is to drift from Module 2 or earlier.

The beam diagnostics systems are described in detail in another paper at this conference. [8] The highlights of the diagnostics are: two bunch-length detectors, 28 stripline beam-position monitors, eight combined-function resistive wall-current monitors/beam-current toroids, eleven three-wire scanners and 35 loss monitors. There are two small dipole trim magnets in each Module, after Sections 1 and 2.

Several aspects of the Linac's control system have been particularly useful during the commissioning and initial operation. It is possible to write simple control loops to run in one of the seventeen local control stations [9]. In particular, much of the reliability statistics, below, have been collected with the aid of various local applications. Also, a gradient-regulation loop was written after the start of commissioning when it became apparent that diurnal temperature variations in the waveguide were causing the gradient to wander in a manner which was objectionable to Booster.

Concerns about personnel and equipment safety, seemingly, have increased in recent years, so the safety systems have received particular attention. It has been necessary to interlock the klystron power to an interlock box [10]. Signals which go into the interlock logic include: the tunnel doors, klystron solenoids, water systems, modulator ready, controls ready, various waveguide spark detectors and waveguide reverse power.

COMMISSIONING

Pre-Commissioning. Final tuning of the first module, which initially was planned to be a prototype, was completed in March, 1991. It was judged to be an adequate "Module 1" by July, 1991. The other modules were then constructed, braised, and power tested. On March 1-13, 1992, an access to the Linac tunnel was made and all seven accelerating modules, the vernier and the buncher were installed in the tunnel alongside the operating 200 MeV DTL tanks. The power systems were connected to the modules at that time, and they were commissioned to their final RF conditioning state *in situ*. The most important aspect of this power commissioning was to demonstrate that the sparking rate could be lowered to acceptable levels, ~0.1% beam loss for the whole linac. All other systems were tested, as much as possible, off line during this period.

Installation. The Fermilab schedule allowed three months, June through August, 1993, to remove the old Linac tanks, install the new SCS cavities, install the diagnostics and quads, and connect the cabling and calibrate the systems. The last four DTL tanks were removed in the first week of the shutdown and the SCS cavities were installed during the next two weeks. At the middle of August, the Linac staff was asked to begin beam commissioning, one week earlier than planned.

Beam Commissioning. Beam commissioning began on August 28, 1993 (evening shift). By August 29 (day shift), 116 MeV beam had coasted though the Linac to the 400 MeV-area dump. Eight days later (September 5), 7 mA of 400 MeV beam was achieved. Studies continued at that current for several days, including a shielding assessment to determine the safety of running at full current. Full current running was allowed and achieved on September 27, less than one month from the beginning of commissioning [11].

Table 3 presents the roster of the people involved with this commissioning. Scientists from SSCL, INR and IHEP, particularly D. Raparia, P. Ostroumov and H. S. Zhang, were crucial for their contributions to the simulations and calculations in preparation for and during commissioning.

Fermilab		
Linac	**Booster**	**Support**
C. Schmidt	**D. McGinnis**	B. Chase
R. Noble	C. Johnstone	R. Pasquinelli
E. McCrory	J. Lackey	F. Harfoush
M. Popovic	R. Tomlin	Ding Sun
T. Kroc	J. Steimel	***AD/Operations***
K. Junck		
J. MacLachlan		
L. Allen		
A. Moretti		
T. Owens		

SSCL	**INR, Moscow**	**IHEP, Beijing**
Linac	**Physics**	**Physics**
D. Raparia	P. N. Ostroumov	H. S. Zhang
J. Hurd	A. V. Feschenko	
F. Guy	S. A. Paramonov	
C. Chang	S. A. Peteronevich	
	S. G. Zharylkapov	
	D. Gorelov	

Table 3., The Commissioning Team for the Linac

Post-Commissioning. Linac commissioning ended, roughly, when the Booster Group started taking most of the shifts, towards the end of September. As Booster began, it became necessary to fine-tune the output parameters of the Linac to improve Booster efficiency. In particular, it was discovered that the beam from the DTL, because of the slow feedback loops in the RF, changed momentum through the Booster beam pulse in an amount comparable to the momentum aperture of that synchrotron. Moreover, the pulse-to-pulse variations in the output momentum were also roughly equivalent to their momentum acceptance. The first problem was fixed by a combination of re-tuning the 201 MHz feedback loops, and by re-tuning and re-casting the feedforward for Module 7 and the buncher. The re-cast involved adding, *ad hoc,* a slope to the feedforward playback which partially compensated for the slope in the momentum through the pulse as it came out of Tank 5. We also discovered, curiously, that the momentum at 400 MeV was particularly sensitive to the phase feedback of DTL Tank 4, and that phase module was replaced.

The long-term pulse-to-pulse variations were traced to the diurnal temperature variations in the waveguide. Two solutions were implemented: the waveguides on the most troublesome systems were water cooled and a software control loop on the cavity gradient, described above, was added.

COMMISSIONING TECHNIQUES

The techniques used to progress through commissioning are detailed here, in rough chronological order.

The first step in commissioning was to allow the 116 MeV beam from DTL Tank 5 to drift through the Linac to the beam dump at the end. This required that the focusing lattice between the two accelerators be measured and matched. The transverse match was measured with the five wire scanners in the transition section and the first module of the Linac, using the Russian matrix code LANA [12] and TRACE-3D [13]. It was necessary to adjust the last few quadrupoles in Tank 5 to obtain a good match. It became apparent at this point that the new Linac was aligned 1 mm below the center line of the old Linac. This made the first new quad, at the output of Tank 5, essentially useless.

Then it was necessary to properly phase the buncher. Several corroborating measurements were performed. First, the point of zero acceleration was determined by observing the beam loading in the RF. The bunching point was determined by crude bunch-length measurements from the wall-current monitors throughout the Linac. This point was also determined by careful time-of-flight measurements. Additionally, the phase-scan signature match algorithm, while not particularly accurate for this non-accelerating cavity, also pointed to the correct bunching phase.

Having phased the buncher, the settings for the first module were calculated. The phase-scan signature match algorithm was used here, and, later, corroborated by the ΔT method [14]. Since phase scan, as it has come to be called, requires that the accelerating phase of the tank be varied over nearly 360 degrees, much of that measurement relies on clean transmission through the tank in quite abnormal circumstances, otherwise the cavity sparks down from the beam losses. The first phase scan could only be done for about 30 degrees around the proper accelerating phase, but this was adequate to get the initial settings. (The transverse and longitudinal match has improved since then, so it is now possible to do a full phase scan at 10 mA without sparking.) Once Module 1 was tuned, the other six modules were tuned rather quickly. The phase scan for Module 2, a striking example of this method, is shown in Figure 2.

After 400 MeV beam was achieved, a second round of phase scans were done for each tank, paying careful attention to consistency. In particular, we measured that allowing the beam to drift through, and potentially give up energy to, a module does not impact the measurement at all. At this time, we measured the output energy of Tank 5 by several methods, including time-of-flight measurements using the BPM plates and the wall-current monitors. We attempted to correct the energy out of Tank 5 (it was too low), but were unable to reliably get it to stay at the required gradient. Consequently, we used the buncher to make up the small energy difference to be properly captured by Module 1.

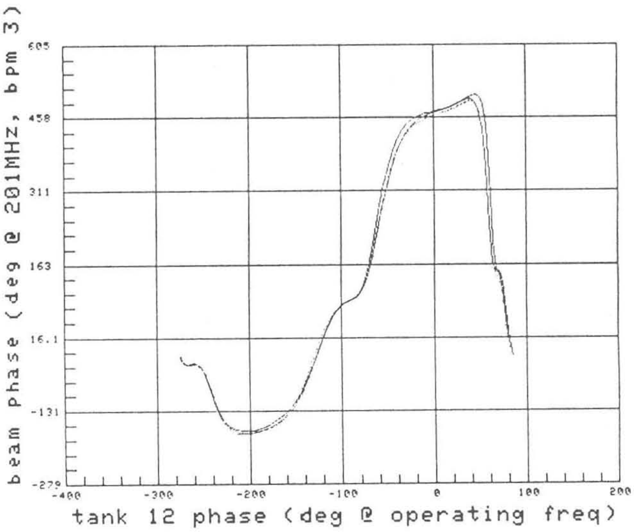

Figure 2, Phase-scan signature match for Module 2 in the 805 MHz half of the Fermilab Linac.

A small, systematic layout problem in the bridge couplers caused the overall length of the accelerator to be small by about 1 cm. The effect of this error was to reduce the synchronous energy at the input to the first module of the SCS. The ΔT code became available at this time and was used to cross-check the phase scan prediction [15].

A steering algorithm was developed [16] and implemented for the Linac. It measured the response of each BPM to small changes in each of the trim magnets, and then calculated the best values for each trim magnet so that the deviation from the centerline is minimized. The centerline of each BPM was determined by minimizing the losses at each point in the Linac.

OPERATION/RELIABILITY

The Linac has quickly faded from the attention of the operations staff at Fermilab because of it's good reliability record. The downtime for the entire period since October for the Linac has been 2.7%; the reliability for the past seven months has been 1.65%. This downtime is split almost equally among the new Linac (0.802%), the old DTL components (0.909%), the preaccelerator (0.487%) and everything else (water, magnets, etc., 0.563%). The alarm reporting to the operators in the early stages was a bit overzealous, so we tailored these alarm messages to the operators so that short failures (like a spark) do not get reported at all.

The number of RF pulses and several varieties of RF and cavity sparks are recorded daily by the control system. These results are summarized in Table 4. Our sparking rate is significantly under the 0.1% goal. These data exclude five days of longitudinal studies in February, 1994.

Module #	RF Pulses	# Sparks	Rate
1	2.002 E8	20035	0.01%
2	2.003 E8	6745	0.003
3	2.006 E8	20608	0.01
4	1.989 E8	8060	0.004
5	1.995 E8	7674	0.004
6	1.989 E8	4007	0.0002
7	1.995 E8	1019	0.00005
Total	***1.398 E9***	***68148***	***0.034%***

Table 4., Sparking rates for the SCS Modules in the Linac, excluding study days

We also measure the number of lost beam pulses in the Linac. A lost beam pulse is defined as any pulse which is seen on the first toroid of the new Linac but not seen at 400 MeV. This is presumed to be caused by sparking in the SCS. The median number of pulses per day which satisfy this criterion is 10. We typically run 25000 400 MeV linac pulses per day for high-energy physics operations. This 0.04% rate, equal to the overall sparking rate, indicating that sparking is independent of the presence of beam.

There have been a few places in the system, in particular, in the modulator, where components have failed prematurely. We obtained a bad batch of magnetics, which have been replaced. The design of the PFN is undergoing some minor modifications now. We monitor the perveance of the klystrons--there has been no sign of degradation so far.

The impact of the 400 MeV Linac has been felt clearly in the Tevatron. It was anticipated that the Booster beam intensity would increase by 75% with the new injection energy. This has been fulfilled. The intensity of beam in the Main Ring has increased by 50% so far. The remaining increase will come when Booster installs new damper systems to reduce the longitudinal and transverse beam blowup during acceleration. The intensity gains in 150 GeV Main Ring have resulted in increased intensities for the coalesced bunches of protons in the 900 GeV Tevatron, which roughly translates to a 100% increase in the luminosity delivered to the two large collider experiments. The anti-proton production rate, however, has not significantly been impacted by the increased beam on target. This work is proceeding.

CONCLUSION

The Fermilab 400 MeV Linac was installed and commissioned during the second half of 1993. The time tables set forth by laboratory management were easily met, and 400 MeV beam, at full beam current, was achieved in three weeks from the start of beam commissioning--less than 4 months from the last 200 MeV beam was seen in the old Linac. The techniques used to commission the Linac were a mixture of old, tried-and-true methods and a few new ideas. The impact of the new Linac has been clearly felt in many aspects of the operation of the Fermilab Collider.

ACKNOWLEDGMENTS

I would like to thank the members of the Linac Department for their help in the preparation of this paper. They are: C. W. Schmidt, M. Popovic, K. L. Junck, L. Allen, A. Moretti, T. Kroc, J. MacLachlan and R. Noble. I, and the rest of the Linac Department, would like to strongly reiterate our deep appreciation to the scientists and their institutions for their incalculably helpful contributions during the time before and during commissioning. In addition to the names given previously, A. V. Feschenko, INR, and J. Hurd, SSCL, deserve specific mention.

During the exciting time of planning and commissioning a new accelerator, sometimes our forgotten partners are our spouses and families. I wish there was some means by which they could truly get significant recognition in this process. This paragraph is an attempt to properly thank these crucial contributors!

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[1] "The 400 MeV Linac Upgrade at Fermilab", Robert J. Noble, Proceedings of the 1992 Linac Conference (Ottawa), p 565

[2] Fermilab Linac Upgrade Conceptual Design report.

[3] "Phase Scan Signature Matching for Linac Tuning," T. L. Owens, M. Popovic, K. Junck, T. Kroc, E. McCrory, this conference.

[4] "Linac Upgrade Module Temperature Control System," FNAL Specification # 1302-ES-296036, Oct 23, 1993.

[5] Interestingly, the cooling for Varian's off-the-shelf version of the 0.2 MW klystrons is vapor cooling, because the average UHF station at that end of the dial (channel 58, I believe) cannot afford the extra water an enclosed system requires!

[6] "H. Pfeffer, et al., "Solid State 24 MW Modulators for Fermilab's 400 MeV Linac," Twentieth Power Modulator Conference (Myrtle Beach), June 1992.

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[8] "Performance of the Beam Diagnostics Systems for the Fermilab 400 MeV Linac," E. McCrory, C. Schmidt, M. Popovic, K. Junck and L. Allen, Poster TH-75.

[9] "Upgrading the Fermilab Linac Control System," E. McCrory, R. Goodwin, M. Shea, Proceedings of the 1990 Linac Conference (Albuquerque), pp 474-476.

[10] The interlock box was built at Fermilab by S. Tawser.

[11] Full current was technically feasible by about September 10, but the mandated "safety envelope" for the new accelerator prevented this from being achieved.

[12] Obtained from P. Ostroumov.

[13] "Trace-3D," K. R. Crandall, LANL Doc. LA-11054-MS, 1987

[14] "The Delta-T Tuneup Procedure for the LAMPF 805 MHz Linac," K. R. Crandall, LANL Report LA-6374-MS, June 1976

[15] A complete comparison of phase scan to delta-T is underway.

[16] "Beam Position Correction in the Fermilab Linac," K. L. Junck, E. McCrory, this conference, poster TH-76.