COMMISSIONING OF THE IUCF 7 MeV H$^-$ LINAC

D.L. Friesel, Indiana University Cyclotron Facility, Lane, Bloomington, IN 47408,
and R.W. Hamm, AccSys Technology Inc, Pleasanton, CA 94566

Abstract

Construction of a 2.24 T-m, rapid-cycling booster synchrotron (CIS) to inject polarized ions (p, d) into the Indiana Cooler [1] is nearing completion at IUCF. Designed to provide 2.5×10^{10} particles per pulse for Cooler injection, the booster is also well suited for use as a source of 60–220 MeV protons for medical therapy. An AccSys Technology Model PL-7 Linac consisting of a 3 MeV RFQ coupled to a 4 MeV DTL is used to pre-accelerate H$^-$ ions to 7 MeV for strip injection into CIS. Two 350 kW, 425 MHZ rf amplifiers power the Linac, which accelerates variable pulse width H$^-$ beams with duty factors up to 0.2%. The Linac accepts up to 1.0 π mm mrad (norm), 25 keV H$^-$ beams and accelerates them to 7 MeV with 1% energy spread and no emittance growth. Following delivery to IUCF in December, 1996, beam commissioning began in January, 1997. The measured Linac beam performance characteristics from this work are presented.

1 INTRODUCTION

The low intensity of even the most advanced polarized ion sources ($\sim$ 1 mA) requires the use of H$^-$ strip injection and accumulation to reach the intensity goal for **CIS** [2]. Intensity gain calculations for H$^-$ ions on thin Carbon foils ($\leq$2–8 μgm/cm^2) as a function of energy indicate that greater than 3 MeV was needed to insure $\geq 10^{10}$ protons per pulse from CIS for Cooler injection [3]. Hence, an AccSys Technology, Inc [4] 7 MeV H$^-$ Linac consisting of a 3 MeV RFQ coupled directly to a 4 MeV DTL was selected as an H$^-$ pre-injector. IUCF and AccSys entered into an “Industrial Partnership” agreement in June, 1995, whereby AccSys designed and built the Linac accelerating structures and power amplifiers and IUCF supplied the H$^-$ source and LEBT, RFQ vacuum tank, all major commercial equipment (power supplies, pumps, etc) and manpower support. Specifications for the Model PL-7 Linac are listed in **Table I** and a layout of the H$^-$ source, LEBT, Linac and7 MeV injection beam line is shown in Fig. 1. The fully assembled Linac (serial No. 001) was delivered to IUCF on December 13, 1996 and installed between the waiting 25 keV H$^-$source and 7 MeV injection beam line. Beam commissioning began on January 12, 1997 and concluded with the injection and accumulation of both 3 and 7 MeV protons in the **CIS** ring this April.

2 LINAC DESCRIPTION

The 4 RFQ vanes are fabricated from copper plated, precision contoured aluminum extrusions with continuous water cooling paths near the vane tips. The stainless vacuum vessel has a removable lid so that the patented self aligning $q/A = 1$ vanes can be replaced with $q/A = 1/2$ vanes for the later development of deuteron beams in CIS. A full scale, low rf power aluminum model of the DTL tank and drift tubes was used to measure frequency response and finalize the mechanical dimensions of the resonator tank and endplates. Each of the 22 water cooled, Cu plated stainless drift electrode assemblies house permanent magnet quadrupoles for transverse focussing. The RFQ and DTL were fabricated separately and assembled on a common rigid support structure with no matching beam line between them. Matching the 3 MeV RFQ exit beam to the DTL acceptance is done in the last few cells of the RFQ. A closed loop water/glycol cooling system regulates both resonator temperatures to $\pm 1^\circ$ C.

The 350 kW rf amplifiers (1 each for the RFQ and DTL) are upgraded versions of an AccSys Technology three stage amplifier based on the EIMAC YU-176 planar triode tube. The final 12 tube amplifier is designed for quick tube replacement and to operate with several failed tubes if necessary. RF power is delivered to the cavities via 3-1/8 inch semi-rigid coaxial cables and side mounted cavity drive loops. The DTL tank is fitted with a slug tuner which has a ±100 kHz tuning range. These amplifiers define the duty factor limit for the Linac.

Each amplifier is equipped with an enhanced Instrument Monitor and Control Unit (IMCU) which communicates with the CIS VISTA controls system [5] via a MIL-STD-1553B bus interface. The IMCUs contain hardware interlocks and electronic monitoring and controls for all Linac functions, including the vacuum systems. In **CIS**, software programs were developed to control, monitor and record amplifier tube operating parameters and spark information, and to automatically recover from VSWR and tube sparkdown faults. The information provided by the IMCU’s and the effective architecture of the amplifier cabinets greatly simplified trouble shooting during initial commissioning of the Linac.

3 LINAC PERFORMANCE

The 25 keV unpolarized H$^-$ source and LEBT was designed to match the input beam requirements specified by AccSys for the RFQ. Built at IUCF, it routinely delivers 0.4 mA peak intensity, 0.6 π μm (norm), 25 keV H$^-$ beams at $\leq$5 Hz with 125 mrad symmetric convergence and 2.5 mm diameter to the RFQ entrance [6]. The source, RFQ and DTL triggers and pulse widths are independently adjustable via the CIS timing system. An example of the rel-

0-7803-4376-X/98/$10.00 © 1998 IEEE

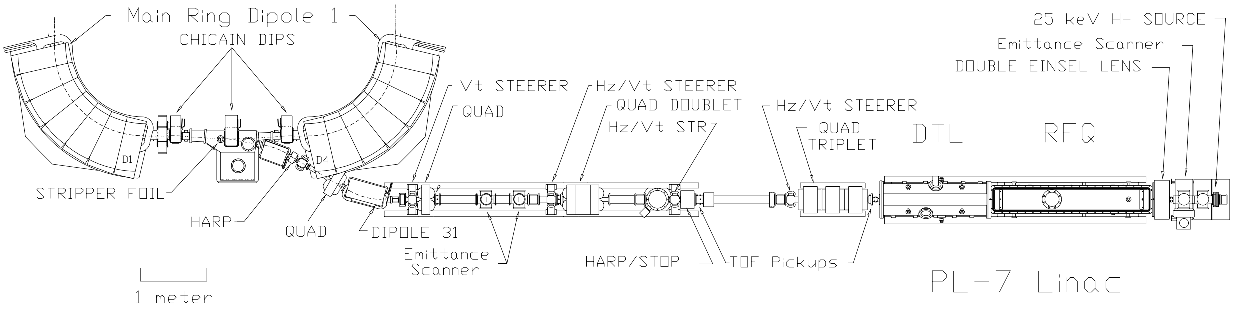

Figure 1: The CIS keV H^- Source, 7 MeV PL-7 Linac and injection beam line through the CIS ring injection straight section.

ative timing sequence used for these devices is shown in Fig. 2.

Table I: PL-7 Linac Performance Specifications

I. Linac (RFQ and DTL)	
Operating Frequency	425 MHZ
Duty Factor	$\leq$0.2%
Design Repetition Rate (variable)	1–5 Hz
rf Pulse Width (variable)	35–300μs
Overall Linac Length	3.979 m
Operating Vacuum (oil Free)	0.08 μTorr
Min. Guaranteed H^- Beam Transmission	$\leq$80%
Design Intensity Range	.1–1.0 mA
II. RFQ Properties	
Input Energy (H^-)	25 keV
Acceptance (norm.)	1.0 π
Vane average Bore Radius	2.48 mm
Inter-vane Voltage	71 kV
Maximum rf Power	0.3 MW
Cavity Q	7350
Output Energy	3.0 MeV
III. DTL Properties	
Input Energy (H^-)	3 MeV
DTL Cavity Q	48000
Maximum rf Power	0.3 MW
Output Energy (H^-)	7.0 MeV
Nominal Energy Spread (T)	$\pm$70 keV
Output Emittance (norm.)	1.0π

The DTL cavity field duration is longer than the RFQ field because 3 MeV H^- beam passes unattenuated through the unpowered DTL cavity, resulting in both 3 and 7 MeV H^- beam from the Linac entering the injection beam line. The source pulse, however, must also begin after the DTL cavity has reached full field. Injection of H^- beam prior to the DTL cavity field reaching full potential clamps the field to zero volts, presumably due to multipactoring. (Initial application of full power to the RF accelerating structures required less than 1 hour of conditioning) De-tuning the source beam and extended DTL operation at full field to condition against multipactoring have not stopped this effect, which was not observed with positively charged proton beams at AccSys. While surprising, this is not a liability for our application because the Linac duty factor is larger than required for CIS injection.

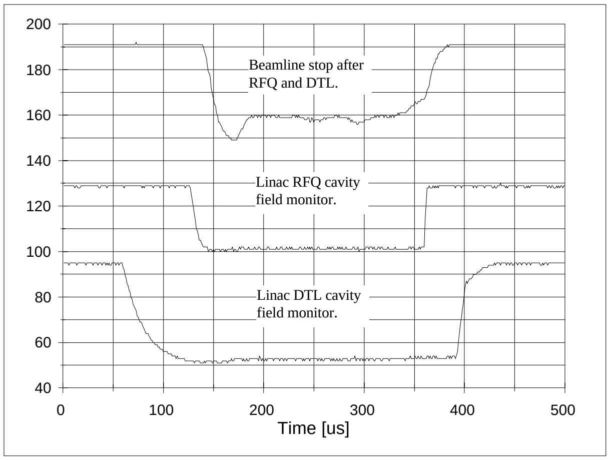

Figure 2: Source, RFQ, and DTL Pulse Sequence

3.1 *RFQ and DTL Cavity Threshold Voltage Measurements*

The required **CIS** injected beam properties are achieved from the Linac only when operated at the design (threshold) cavity field with all 7 amplifier feedback loops (frequency, phase, and cavity field) closed and operating properly. The PL-7 threshold voltages were measured open-loop at AccSys with protons and again with all 7 amplifier loops closed at IUCF with H^- ions using the diagnostics in the CIS injection beam line shown in Fig. 1. Beam transmission through the Linac increases with RFQ cavity field until the threshold pickup voltage of $V_o = 4.35$ V is reached for both measurements, as shown in Fig. 3, and requires 295 kW of rf power, slightly higher than the predicted 284 kW. The DTL V_o was determined by measuring the H^- beam energy as a function of the its cavity field as determined by the beam position on a multi-wire HARP at the exit of a 31° bending magnet and the output of a beam TOF energy measurement system. These only measured energy changes, and could not be used to precisely determine beam energy. The data for several measurements are shown in Fig. 4. The DTL Vo of 3.57 V is obtained at an amplifier output power

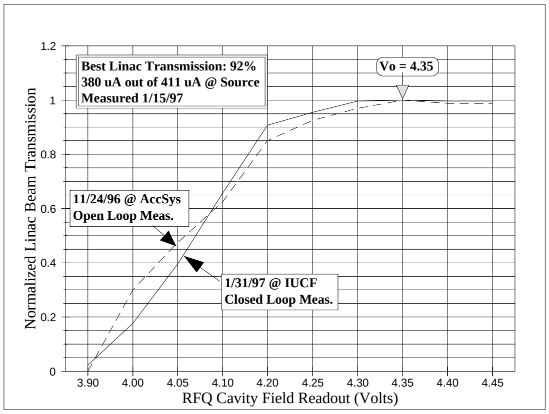

Figure 3: RFQ Threshold Measurement

of 300 kW, also higher than predicted. The beam energy at these threshold values was later determined to be 6.987 MeV by measuring the orbit period of circulating beam in the ring.

3.2 *Linac Transmission and Accelerated Beam Properties*

Beam property measurements were made at both 7 and 3 MeV by running with both RFQ and DTL cavity fields set to their V_o and by turning the DTL cavity field off and scaling the beam line accordingly. Beam transmission from the source to a compensated beam stop located 2.5 m from the Linac exit range from as high as 90% to as low as 75% from run to run. Typically, 320 μA of the 400 μA available at the source are recorded on this stop. The beam profile measured on a multi- wire HARP in front of this stop is a 6 mm (FWHM) waiste as predicted for the calculated currents in the quad triplet at the Linac exit, verifying that the optical properties of the accelerated beam their are as predicted by AccSys. Beam transmission from this stop to the stripper foil in the CIS injection region is typically 80%, again with all beam line focussing elements operating within 5% of the values calculated using the AccSys beam focussing predictions. Similar transmission is achieved for 3 MeV H^- with beam line quads operating within 10% of the values scaled from 7 MeV.

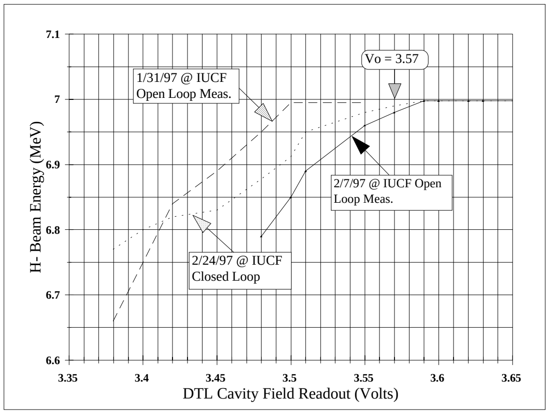

Figure 4: DTL Threshold Measurement

Both the 3 and 7 MeV H^- beams have been injected and accumulated in the CIS ring [7]. Over 250 uA (peak) of protons of the 400 uA H^- available at the source are strip injected into the CIS ring, as measured on a compensated stop between ring main dipole magnets 1 and 2. The beam profile on the foil is a 6 mm dia double waste. Alignment of the source, Linac and injection beam line is excellent, as beam steering requirements are minimal. The 7 MeV H^- horizontal beam emittance was measured on several occasions to be $\leq 1.0\ \pi$ mm mrad (norm.), also as predicted.

3.3 *Amplifier Feedback Loop and Beam Stability*

The Linac amplifier feedback loops required continued development at IUCF to get the optimum 7 MeV H^- beam properties desired for CIS injection. Primarily, the specified beam energy, energy spread and emittance are required to maintain stable strip injection into the ring. The measured stability of the feedback loops for both amplifiers are $\pm 2^\circ$ phase and $\pm 0.5\%$ amplitude. The stability of the RFQ-DTL relative phase loop, also important to maintain energy stability, is about $\pm 2^\circ$, as determined by the beam energy stability using the beam line TOF system. These closed loop operating parameters provide reproducible and stable beam injection into the CIS ring [2]. A beam energy spread measurement has not been made, but is likely near the specified $\pm 1\%$ based on initial ring strip injection performance studies. Occasional departures from the RFQ/DTL relative phase stability are observed during operations, which significantly reduces injection efficiency. Development work is continuing to improve the long term performance of the feedback loops and the Linac beam stability.

4 ACKNOWLEDGMENTS

The present performance of the PL-7 Linac is the result of the support provided by AccSys Technology, Inc and the dedicated and competent efforts of the IUCF technical and professional staff. Their efforts contributed significantly to the timely commissioning of the ring injection system this April. Supported by Indiana University and National Science Foundation Grants NSF PHY 93-147-83 & 23-423-10.

5 REFERENCES

[1] R.E Pollock, IEEE 89CH2699-0, 17 (1989).

[2] D.L. Friesel and S.Y. Lee, IEEE 95CH35843, 336 (1995).

[3] K. Hedblom, IEEE 95CH35843, 1861 (1995).

[4] AccSys Technology, Inc, 1177 Quarry Lane, Pleasanton, CA 94566

[5] J. Callahan *et al*, “A High Reliability Accelerator Control System”, this publication.

[6] V. Derenchuk *et al*, “Pulsed Ion Sources for the IUCF Cooler and Injector Synchrotron”, this publication.

[7] D.L. Friesel *et al*, “ Status of the IUCF Cooler Injector Synchrotron ”, this publication.