PERFORMANCE OF AN *AccSys Technology* PL-7 LINAC AS AN INJECTOR FOR THE IUCF COOLER INJECTOR SYNCHROTRON

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Abstract

An AccSys Technology Model PL-7 Linac is used to pre-accelerate H^- ions to 7 MeV for strip injection into a new 2.4 T-m injector synchrotron now being commissioned at IUCF. The Cooler Injector Synchrotron (CIS) is designed to inject over 10^{10} polarized protons or deuterons per pulse at 5 Hz into an existing electron cooled synchrotron-storage ring (Cooler) for nuclear research [1]. The linac, a 3 MeV RFQ coupled directly to a 4 MeV Drift Tube Linac, is designed to transmit over 1 mA of 7 MeV H^- ions to the CIS injection beam line with 85% transmission, 1 π mm mrad normalized emittance and 1% energy spread. Two 350 kW, 425 MHz rf amplifiers power the linac which accelerates variable pulse width H^- ions at duty factors up to 0.2%. We discuss the beam performance of this unique linac after a year of service as a synchrotron injector, and compare measured beam properties with calculations made during design and fabrication.

1 INTRODUCTION

Negative ion strip injection into the CIS booster synchrotron is required by the relatively low intensities ($\leq$ 5 mA) of polarized proton and deuteron beam ion sources. Strip injection and accumulation calculations for H^- ions on thin Carbon foils (2 – 8 μgm/cm^2) predict that a minimum energy of 5 MeV is required to achieve the intensity goals desired for Cooler injection, with higher energies yielding higher intensity gains [2]. This led to the selection of an AccSys Technology Model PL-7 Linac as the H^- pre-accelerator for CIS. The PL-7 linac design consists of a modified AccSys Technology 3 MeV RFQ directly coupled to a 4 MeV, 22 cell drift tube linac. Beam matching from the RFQ into the DTL is done internally at the RFQ exit and the DTL entrance. Indiana University and AccSys technology entered into an "Industrial Partnership" agreement whereby AccSys designed and built the accelerating structures and power amplifiers. IUCF supplied the source, LEBT, RFQ vacuum vessel, commercial hardware and some manpower support. Fabrication of the IUCF 7 MeV H^- linac, the prototype of the present AccSys Model PL-7 design (serial No. 001), began at AccSys in June, 1995 and was completed by December, 1996.

Construction of a booster synchrotron (CIS) to replace the IUCF cyclotrons as an injector for the Cooler [1] began in late 1994. Beam commissioning of the H^- linac pre-accelerator and the ring strip injection system began in January 1997 with a 25 keV unpolarized H^- beam and resulted in the injection, accumulation and capture of both 3 and 7 MeV protons in CIS. Construction of an intense pulsed H^- polarized ion source (CIPIOS) [3] also began in January 1997. Beam acceleration studies beginning in Nov. 1997 resulted in the acceleration of 10^{10} protons to 240 MeV by May 1998. Beam extraction and Cooler injection development will begin during the last quarter of 1998 and CIPIOS will deliver polarized H^- beam to CIS and the Cooler in the first quarter of 1999. The CIS lattice design [4], beam performance goals [5,6], and initial H^- beam strip injection and acceleration commissioning results were previously reported [7,8,9].

2 LINAC DESCRIPTION

Design specifications for the IUCF Model PL-7 Linac are listed in Table I, and were determined from modified versions of the linac design codes PARMTEQ and PARMILA. Beam measurements made during the last year, described below, are compared with these predictions. A layout of the PL-7 RFQ/DTL pre-accelerator is shown in Fig. 1, and details of the 4 vane RFQ and 22 cell DTL accelerating structures and 350 kW amplifier systems are provided in Ref.[7]. The RFQ

TABLE I

PL-7 Linac Performance Specifications and Parameters

RFQ/DTL Operating Frequency		425 MHz
Input Energy (H^-)		25.0 keV
Output Energy (H^-)		7.0 MeV
Duty Factor		≤ 0.2 %
Repetition Rate (variable)		0.1 – 10 Hz
Pulse Width (Variable)		35 – 350 μs
Maximum RFQ and DTL RF Power		0.35 MW
Normalized RFQ Acceptance (90%)		≤1.0 π μm
Normalized DTL Output Emittance (90%)		1.0 π μm
Output Energy Spread		±75 keV
Guaranteed Beam Transmission		≥80 %
A) RFQ Parameters:		
Overall Length:		228.4 cm
-Matching:	1.0 cm	
-Shaper:	22.3 cm	
-Bunching:	17.1 cm	
-Acceleration:	190.1 cm	
Ave. Bore Radius:		0.248 cm
Vane Voltage:		71 kV
Cavity Q:		7547
Peak Operating Power:		295 kW
B) DTL Parameters:		
Overall Length:		153.7 cm
No. Cells:		22
Quad Length (SmCo Perm Magnets):		2.54 cm
Cavity Q:		30,000
Peak Operating Power:		285 kW

for these measurements is designed for q/A=1 particles (H^+, H^-). To accelerate deuteron beams, this structure can be replaced in the RFQ with a separate q/A = ½ structure through a removable lid on the RFQ vacuum vessel.

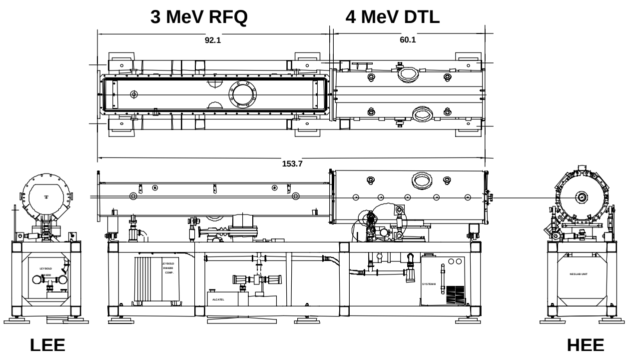

Figure 1. AccSys Technology Model PL-7 7 MeV Linac

3 LINAC PERFORMANCE

For all measurements reported here, a ≤ 1.0 mA peak, 25 keV unpolarized H^- beam from a duoplasmatron source is focused at the entrance of an AccSys Technology model PL-7 Linac. Beam is matched to the Linac (RFQ) acceptance requirements (symmetric 1.3 mm beam radius and 125 mrad convergence half angle, normalized emittance of 1.0 π µm) via a Low Energy Beam Transport (LEBT) system consisting of three Einsel lenses, an x/y steering magnet and an electron beam sweep magnet. Diagnostics including a multi-wire harp, an emittance scanner and a beam stop were designed into the LEBT. Measurements of the 25 keV H^- beam properties at the RFQ entrance are $\varepsilon \leq 0.6$ π µm, $\alpha = 0.62$ and $\beta = 0.012$, well within the AccSys specifications. The small source emittance is not necessarily an advantage for the PL-7 linac, which was designed for an acceptance of 1.0 π µm. The new polarized source, however, will have a beam emittance more closely matched to the PL-7 emittance requirements.

The 425 MHz three stage power amplifiers for the linac must provide the required RFQ and DTL cavity fields with amplitude and phase stabilities of ± 0.5% and ± 0.2^o respectively to achieve the 7 MeV H^- beam properties listed in Table I. Significant improvements to the frequency, phase and amplitude loops were required at IUCF to meet these specifications, which are critical to the injection performance goals for CIS. The frequency and phase loops operate to specification. Until recently, however, the cavity amplitudes were run open loop to achieve the RFQ and DTL required threshold fields because the amplifiers, based on the EIMAC YU-176 triode tube, had insufficient power to maintain stability with these loops closed. The amplifiers must typically run above 295 kW.

The performance of the linac was characterized by measuring the properties of the 7 MeV H^- beam using several diagnostic systems in the 9m transfer beam line between the linac and the CIS ring. The RFQ cavity field threshold (V_o) was determined to be 4.35 V on a diode attached to a small pickup loop by measuring the transmission of beam through the linac with the DTL turned off as a function of cavity field. Typically, beam transmission through the linac is 80%, although transmissions as high as 90% have been observed. Beam time-of-flight pickups in the 7 MeV transfer beam line are used to monitor the energy and energy stability of the beam from the linac. The orbit period of the strip injected proton beam in the CIS ring is also used to independently verify the energy of the H^- beam extracted from the DTL. At the measured DTL threshold diode voltage of 3.57 V, the rf capture frequency of an optimally stored proton beam in CIS is 2.09730 MHz (h=1), corresponding to a circulating proton beam energy of 6.990 MeV. The 7 MeV H^- beam emittance was measured to be between 0.6 and 1.0 π µm.

The FWHM energy spread of the H^- beam was measured to be ± 85 keV via elastic scattering from a 2.5 mg/cm^2 Au foil with planar Si surface barrier stopping detectors at 30^o scattering angles. This slightly larger than the predicted value of ±75 kV by AccSys was caused by our inability to close the DTL amplifier cavity field amplitude loop. This is illustrated in Fig. 2. The upper trace is an oscilloscope display of the TOF energy measurement of a single 200 µsec long, 7 MeV H^- beam pulse from the linac. The two initial peaks in this trace are instrumental “turn-on” noise, while the energy fall off (≈200 keV) during the last 40 µsec is real and mimics the DTL cavity field amplitude fall-off with pulse length. The vertical scale for this trace is 100 keV/div. The lower trace is the intensity of strip injected proton beam in the CIS ring (0.2 mA/div), which exhibits a similar decrease with pulse length that is not evident on the H^- beam stop prior to injection. When amplifier upgrades allowed the amplitude loops to be closed, the TOF energy fluctuations were reduced to 25 keV, which reduced intensity fluctuations for strip injected beams.

These data illustrate the importance of stable linac cavity fields on the injection efficiency of protons into the CIS ring. The TOF energy monitor is continuously displayed during routine CIS operations to diagnose and correct linac (DTL) stability problems. Even with the DTL amplitude loop open, injection stability is quite acceptable for long running periods when the Linac is properly tuned and has reached thermal equilibrium after startup. With the loop closed, accumulated

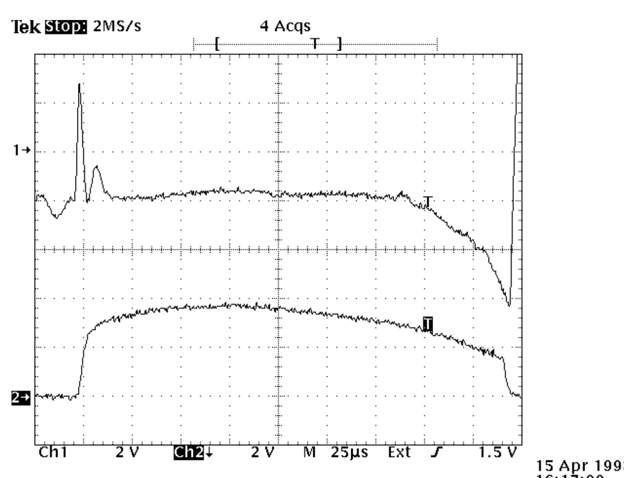

Figure 2. Scope displays of the 7 MeV H^- beam TOF energy (upper) and first turn proton beam intensity in CIS (lower).

and stored beam intensity typically varies by less than a few percent from cycle to cycle.

The focussing properties of the 7 MeV H^- beam exiting the linac were determined to be very close to the predictions provided by AccSys, which were used to design the transfer beam line optics that match the linac beam to the synchrotron acceptance. The beam line focussing elements and measured beam envelope are within 5 % of the values predicted using the optics code TRACE 3D, and beam transmission from the linac to the stripper foil in the ring is better than 85%.

4 BEAM INJECTION & RF CAPTURE

The linac delivers a 300μsec H^- beam pulse on a 4.5 $\mu g/cm^2$ stripper foil in the CIS at up to 5 Hz repetition rates for the injection and accumulation of 7 MeV protons. Two bumpers displace the ring equilibrium orbit onto the foil for strip injection and proton accumulation. Typically, an equilibrium accumulation of 8×10^{10} protons occurs in 200 μsec, after which the bumpers are turned off and adiabatic turn-on of a 1^{st} harmonic rf cavity is started. Only about 2×10^{10} protons are rf captured and stored 2 msec latter because of the short 1/e beam lifetime (< 0.5 sec) in the 0.2 μTorr average ring vacuum. The captured beam bunch factor is 2.5 for an rf cavity voltage of 250 volts.

A schematic diagram of the RFQ, DTL and bumper fields, the linac H^- beam pulse and the injected proton beam accumulation relative timing required for optimal strip injection is shown in Fig. 3. We were surprised to find that the DTL cavity field must be at threshold before the 25 keV H^- beam from the source is injected into the linac or the DTL cavity field clamps to zero. This phenomenon was not observed when testing the linac at AccSys with protons. It is likely that stripped electrons produced in the RFQ cause multipactoring in the DTL which prevent its' rise to full field. This inconvenience was resolved by pulsing the source extraction HV in time with the RFQ cavity field, delayed by

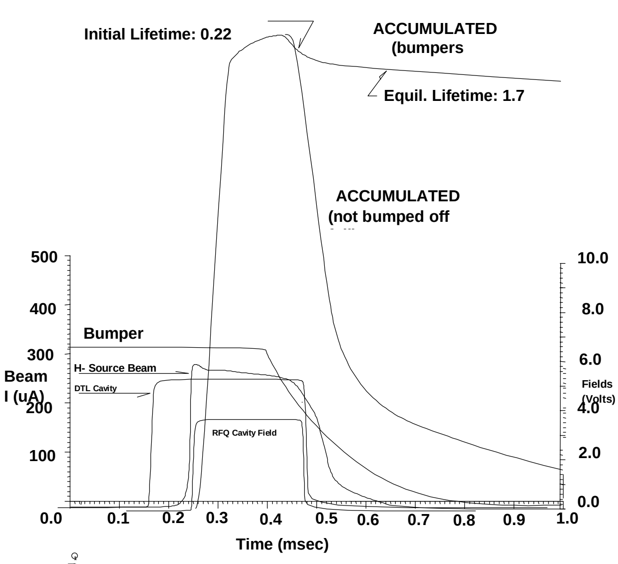

Figure 3. PL-7, bumper, and beam timing diagram.

as little as 30 μsec after the DTL cavity reaches full field. The RFQ pulse width must reside within the bounds of the DTL field anyway to insure that only 7 MeV H^- ions enter the transfer beam line, since 3 MeV H^- ions transmit through the Linac with equal efficiency as 7 MeV ions when the DTL cavity field is turned off.

5 CONCLUSIONS

The PL-7 linac has been used for over 1400 hours during the last year to inject 7 MeV protons into the new IUCF Cooler Injector Synchrotron. While some development of the RF amplifiers was required to achieve the guaranteed beam properties reported here, this linac has proven to be a reliable and stable source of 7 MeV H^- ions for strip injection into CIS. When delivered, the PL-7 linac was yet another new accelerator type introduced into the IUCF inventory. With continuous support from AccSys Technology, we have undertaken the effort to upgrade the amplifiers at IUCF ourselves to facilitate our understanding and maintainability of this system. The accelerating structures have proven to be rugged and reliable while the beam properties from this accelerator are reproducable to the point where no tuning of the transfer beam line and little tuning of the ring injection parameters are required to routinely achieve optimum strip injection performance. Turn-on during startup is usually quick (30 minutes), and once tuned up, the linac performs reliably for long periods of time, becoming invisible during other ring development activities such as beam acceleration and extraction studies. We are confident that these accelerator properties will be maintained as the CIS ring moves from developmental to operational status.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] R.E. Pollock, IEEE 89CH2699-0, 17 (1989).
[2] K. Hedblom *et al.*, IEEE95CH35843, 336 (1995).
[3] V. Derenchuk *et al.*, PAC97, Vancouver, BC, to be published.
[4] D. Li *et al.*, IEEE 95CH35843, 357 (1995).
[5] D.L. Friesel *et al.*, IEEE 95CH35843, 336 (1995).
[6] D.L. Friesel & S.Y. Lee, EPAC'96 Spain, 548 (1996).
[7] D.L. Friesel *et al.*, PAC97, Vancouver, BC, to be published.
[8] D.L. Friesel & R. Hamm, PAC97, Vancouver, BC, to be published.
[9] D.L. Friesel & G.P. Berg, EPAC98, Stockholm, SE, to be published.