COMMISSIONING THE IUCF COOLER INJECTOR SYNCHROTRON

D.L. Friesel and G.P. Berg, Indiana University Cyclotron Facility, Bloomington, Indiana, USA

Abstract

Commissioning of a compact 2.40 T-m synchrotron to inject polarized light ion beams into the IUCF 3.6 Tm electron-cooled storage ring (Cooler) has successfully demonstrated 7 MeV H^- beam strip injection, and proton beam accumulation, adiabatic capture and acceleration of over 10^{10} protons to energies between 50 and 240 MeV. Measured ring and beam parameters agree very well with predictions for this 17.64 m ring, which is also well suited for use in proton therapy and other applications. The results of these commissioning studies and a discussion of beam limiting performance factors in CIS are presented.

1 INTRODUCTION

Construction of the new Cooler Injector Synchrotron (CIS) to replace the IUCF cyclotrons as an injector of polarized proton and deuteron beams into the Cooler [1] began in late 1994 with funding from both the NSF and Indiana University. Beam commissioning of the 7 MeV H^- linac pre-accelerator and the CIS ring strip injection system began in January 1997 with a 0.7 mA peak intensity unpolarized H^- beam simultaneously with the construction of a new pulsed H^- polarized ion source (CIPIOS) [2]. CIPIOS is scheduled to deliver polarized H^- beam to CIS in the first quarter of 1999. The CIS lattice design [3], beam performance goals [4,5], and initial H^- beam strip injection commissioning results [6,7] were previously reported. Beam acceleration studies began in Nov. 1997 following the completion of the ramping control [8] and diagnostic [9] systems and continued until installation of the fast kick extraction hardware began in May 1998. Beam diagnostics available for these tests were 8 x/y BPM pairs located at the entrance and exit of the 4 ring dipoles, a removable multi-wire HARP for viewing first-turn and multi-turn proton beam injection, a betatron tune kicker system and a WGM for viewing beam intensity and pulse shape. A schematic of the CIS ring showing the location of the injection, extraction, acceleration and diagnostic elements is provided in Fig. 1. The injection and adiabatic capture efficiency and acceleration performance of the CIS ring are discussed in this report.

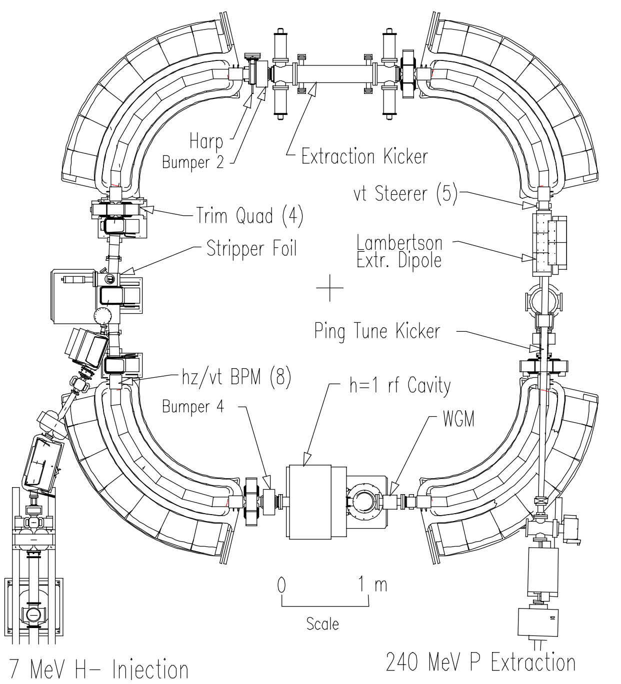

Figure 1: CIS Ring layout showing diagnostic elements.

2 BEAM INJECTION & RF CAPTURE

A 0.70 mA peak, pulsed, 25 keV H^- beam from a duoplasmatron source is focused at the entrance of an AccSys Technology model PL-7 Linac consisting of a coupled 3 MeV RFQ and 4 MeV DTL. Beam transmission through the 3.98 m linac is better than 80% when the 425 MHz RFQ and DTL amplifiers provide the required 300 kW of rf power with all 7 frequency, amplitude and phase feedback loops closed and regulating. The FWHM energy spread of the 7 MeV H^- beam was measured at a double waist 2.5 meters from the linac exit to be $\leq$ 150 keV via elastic scattering from a thin gold target, and is in good agreement with design specifications. A 425 MHz de-buncher, presently under construction, will be located at this double waist to minimize the beam energy spread at the CIS injection straight, another 7.5 m away. The normalized emittances of the 25 keV and 7 MeV H^- beams were measured to be 0.6 $\pi\mu$m and 1.0 $\pi\mu$m, respectively, also within manufacturer specifications.

The linac delivers a 200μsec H^- beam pulse on a 4.5 $\mu g/cm^2$ stripper foil in the CIS injection straight at up to 4 Hz repetition rates for the injection and accumulation of 7 MeV protons. Two bumpers in ring sections 2 and 4 displace the ring equilibrium orbit onto the stripper foil for beam injection and accumulation. Typically, an equilibrium accumulation of 8 x 10^{10} protons occur in ≅175 μsec, at which time the bumpers are triggered off and adiabatic turn-on of the 1st harmonic rf cavity is started. The 1/e lifetime of the captured beam varies from 0.22 seconds immediately after capture to an equilibrium value of 1.72 seconds 200 msec later for an average ring vacuum of 0.2 μTorr. Beam acceleration is initiated within a few μsec of rf capture, by which time lifetime losses have reduced the stored beam to ≅2 x 10^{10} protons. The stored beam energy is measured via the orbit period to be 6.987 MeV. The ring fractional tunes at this energy are 0.456 horizontally and 0.780 vertically, and are in excellent agreement with the lattice design calculations. The captured beam bunching factor is 2.5 for an rf cavity voltage of 250 volts, and the beam diameter during accumulation as seen on the multi-wire harp in section 2 is 3 cm in diameter.

No measurement of the injected and accumulated beam emittance is possible with the available diagnostics in the CIS ring, although plans are to measure the emittance of the 7 MeV kick extracted beam immediately after accumulation when the extraction hardware is completed. Beam centering at injection is accomplished with no ring vertical steering and < 0.02% corrections of the 4 main dipole currents.

3 BEAM ACCELERATION

The ring main dipole current as a function of Bρ for ramping is derived from extensive field mapping data [10], and is characterized by a 12-parameter polynomial fit of the 4-magnet average. Bρ is defined to vary as the sine to the n^{th} power of the up-ramp time, which is divided into 96 time intervals called ramp vectors. Thus dBρ/dt for the first 300 msec of the ramp can be varied from < 0.5 Tm/s for n=5 to > 4.0 Tm/s for n=1 for a 1 sec ramp from 7 to 200 MeV protons. This provided widely variable starting ramp rates for initial ramp development with no operating beam phase or radial position feedback loops. Referred to as the "ramp power", n is continuously variable from 1 to 5, and can be easily changed in the ramp calculation software. The software calculates both main dipole current and rf cavity frequency as a function of Bρ during the ramp and creates a ramp table of 96 vectors for each. Beam centering in the ring during the ramp is monitored by 8 x/y BPM pairs and is maintained by manually making small adjustments (<0.4%) to the rf cavity frequency ramp vectors. Modifications to the calculated dipole current ramp vectors are possible but complicated because the magnet inductance varies with excitation.

3.1 Beam Acceleration Performance

Beam was ramped from 7 to 50 MeV for the first time on Nov. 4, 1997. In subsequent development runs, protons were sequentially accelerated open loop (no beam phase feedback) to 100, 150, 175, 200, 225, 235 and 240 MeV with ≥ 80% transmission of the RF captured beam with no hexapole or trim quad corrections, verifying that the field properties of the 4 main ring dipoles are nearly identical and very close to the design fields calculated using the 3D Laplace code *MagNet*. The measured ring fractional tunes vary by ≤0.01 and beam centering is maintained to ± 5 mm during acceleration with no main dipole trim coil or vertical steering corrections. The addition of a beam phase feedback loop to the RF system marginally improves ramp transmission. The measured 1/e lifetime of 225 MeV proton beams in the 0.2 μTorr ring vacuum is 573 sec.

The RF frequency corrections required to maintain beam centering during ramps to 150, 175, 200 and 240 MeV are compared in Fig. 2. The frequency vector corrections are quite similar from vectors 28 to 75, but are markedly different at the beginning and end of the ramps. The ramps to 175 and 240 MeV were done at n=1.7, while the 150 and 200 MeV ramps were done at n=2. The resulting starting dB/dt differences explain the two correction patterns observed between vectors 0 and 28. The vector correction differences at the ramp ends are caused by a reduction in the dipole effective field length with increasing magnet saturation for energies above 150 MeV. The resulting reduction in orbit circumference from 150 to 240 MeV is 0.4%, which is reflected in the RF frequency vector corrections shown in Fig. 2. Although the ramp ends at vector 96 (typically 1 second), frequency corrections are required for up to 20 additional vectors (≈200 msec) to compensate for dipole field drift at the flattop.

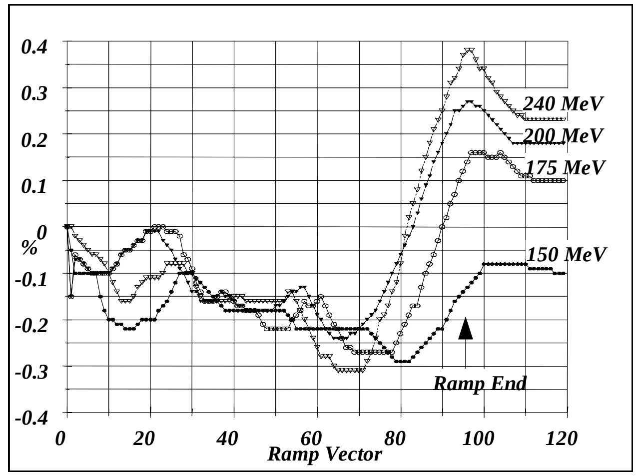

Figure 2: RF frequency corrections (%) as a function of ramp vector number for several flattop energies.

The main dipole power supply, acquired surplus from FNAL, has sufficient capacity to ramp protons to 250 MeV, although the magnets are already driven well into saturation at 1.87 T for 240 MeV protons. The transition energy is calculated to occur at 256 MeV. For 220 MeV protons, the dipole field is 1.783 T, the highest field mapped for the main ring dipole. The radial field variation (dB/B) across the central 9 cm of the pole tip here is 0.1% and is virtually pure hexapole. Magnet end profile compensation is employed to reduce the integrated hexapole component to $k_2 \cong -0.05\ m^{-3}$ for fields up to 1.5 T. It then falls rapidly to $-0.55\ m^{-3}$ at 1.783 T, at which point the calculated ring dynamic aperture is still larger than the 5 cm x 10 cm vacuum chamber.

3.2 Ramp Transmission Losses

A low impedance Wall Gap Monitor (WGM) is used to measure the ring orbit period, bunching factor and intensity during ramping. For proton energies above 175 MeV, all beam losses occur during the first 200 to 300 msec of the ramp, as shown in Fig. 3. Increasing the ramp rate at low energies by reducing the "ramp power" (n) from 5 to 1.5 improves ramp transmission, while energizing the hexapole coils mounted on the dipole vacuum chambers to counteract the dB/dt induced eddy current hexapole components produced no effect. Hence, it appears that these transmission losses are caused by the short beam lifetime at the lower energies. This was verified by reducing the time between

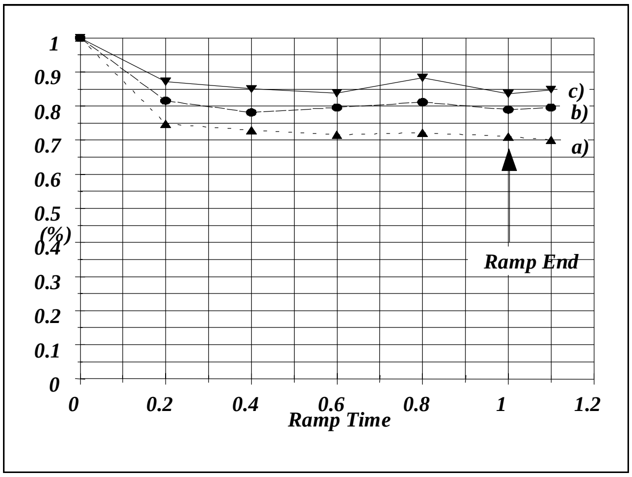

Figure 3: Beam transmission for one second ramps to 225 MeV for 3 values of RF acceleration voltage (see text).

adiabatic capture and the initiation of acceleration to a few μsec, which did not improve ramp transmission, but did increase the amount of beam reaching the flattop energy. The predicted vertical emittance growth of a circulating 7 MeV proton beam in a 0.1 μTorr vacuum for 200 msec is 5.5 πμm, which is 25% of the growth calculated for 350 passages (175 μsec accumulation) through the 4.5 $\mu g/cm^2$ carbon stripper foil. The vertical emittance growth during strip accumulation is the intensity limiting mechanism for the CIS ring.

Ramp transmission was also measured as a function of RF cavity voltage. In Fig. 3, proton beam transmissions for acceleration from 7 to 225 MeV is plotted for three rf cavity voltage ramp profiles as a function of ramp time; a) a constant 250 V, b) rf cavity volts increased linearly with ramp time from 250 to 500 V, and c) a constant 500 Volts. The ramp power (n) for all three cases was 2, and the strip inject, adiabatic capture and acceleration start times and durations were adjusted to maximize the beam available at the ramp start (~ 1.5×10^{10} protons). The measured bunching factor varies from 2.5 at injection to 4.5 at 225 MeV nearly independently of the RF cavity voltage profile used.

A beam intensity profile for an optimized one-second ramp to 225 MeV as observed with the WGM is shown in Figure 4. The pulse amplitude increase observed during the ramp is a combination of the increasing bunching factor and particle velocity during acceleration. A log conversion of the pulse amplitude observed during acceleration is also plotted with the raw WGM output. The number of protons at the 225 MeV flattop is 1.1×10^{10}, corresponding to 18 mA of circulating beam current in the CIS ring.

4 BEAM EXTRACTION STATUS

Single turn fast-extraction is accomplished via a 1.3 m long stripline kicker driven by a bipolar output Blumlein pulse modulator [11] which provides ±55 kV, 330 nsec long pulses with ≤25 nsec rise times. The kicker produces a 17 mrad deflection 3 m downstream, displacing the beam across the septum of a vertical Lambertson extraction magnet which steers the beam into the transmission line to the Cooler. A 225 MeV proton beam has a 97 nsec orbit period and a bunching factor of 4.5.

The fast kicker was installed in the ring in May, and beam was injected and accelerated through its 4 cm wide horizontal aperture with no reduction in accumulation or ramp transmission. The pulse modulator is undergoing tests and will be installed in the CIS ring along with the Lambertson extraction dipole in July, after which extraction studies will begin.

5 ACKNOWLEDGEMENTS

The work reported here was made possible by the skill and dedication of the technical and profession staff of IUCF, who were involved in all phases of this construction and commissioning effort. We also wish to thank Professor S.Y. Lee and his graduate students for their theoretical support for the ring performance predictions.

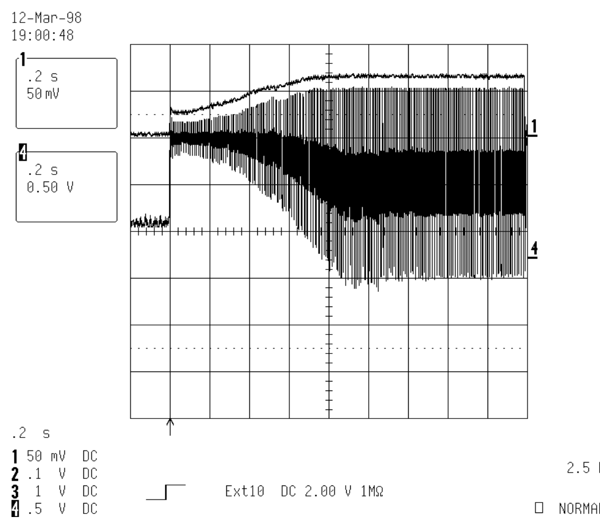

Figure 4: WGM out put for 225 MeV Proton beam ramp.

6 REFERENCES

[1] R.E. Pollock, IEEE 89CH2699-0, 17 (1989).
[2] V. Derenchuk *et al.*, PAC97, Vancouver, BC, to be publ.
[3] D. Li *et al.*, IEEE 95CH35843, 357 (1995).
[4] D.L. Friesel *et al.*, IEEE 95CH35843, 336 (1995).
[5] D.L. Friesel & S.Y. Lee, EPAC'96 Spain, 548 (1996).
[6] D.L. Friesel *et al.*, PAC97, Vancouver, BC, to be publ.
[7] D.L. Friesel & R. Hamm, PAC97, Vancouver, BC, to be published.
[8] J. Callahan *et al.*, PAC97, Vancouver, BC, to be publ.
[9] M. Ball *et al.*, 8th Beam Instrumentation Conf, Palo Alto, CA, May 4-7, 1998, to be published.
[10] G.P.A. Berg *et al.*, PAC97, Vancouver, BC, to be publ.
[11] J.F. Power, *et al.*, IEEE Vol. NS-32 3021 (1985).

*Supported by National Science Foundation Grants NSF PHY 93-147-83 & 23-423-10