INITIAL PERFORMANCE OF THE IUCF COOLER INJECTOR SYNCHROTRON[*]

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Abstract

Construction of a compact 2.4 Tm Cooler Injector synchrotron (CIS) to injection intense polarised proton and deuteron beams into the IUCF 3.6 Tm electron cooled storage ring (Cooler) is complete. Beam commissioning began in 1997 with unpolarized H⁻ strip injection and progressed to the extraction of 210 MeV protons from CIS and the injection of 10^{10} protons at 200 MeV into the Cooler for experiment. With a circumference of 17.36 m, CIS is possibly the smallest and least expensive example of this accelerator type for protons, and may serve as a practical proton source for medical and other applications. This contribution discusses our design choices, the resulting technical and fabrication challenges, and their solutions. Emphasis is given to the CIS ring beam performance from 7 MeV H⁻ injection through Cooler 200 MeV proton injection and accumulation.

1 INTRODUCTION

A compact synchrotron to replace the Indiana k220 cyclotron as an injector of polarised protons and deuterons into the Cooler [1] was jointly funded by Indiana University ($1.5 M) and the NSF Academic Research Infrastructure Program ($2.0 M) in August of 1994. The primary goal was to inject over 10^{10} polarised particles/pulse into the Cooler to improve experimental luminosity for medium energy cooled beams on thin internal targets. Initial CIS design parameters were influenced by the relatively low intensities available from pulsed polarised ion sources ($\approx$1 mA peak) and by the desire to avoid an intrinsic depolarising resonance in the Cooler for 186 MeV protons. A secondary goal was to simplify the Cooler injection process for polarised beams to reduce machine overhead and increase experimental duty factor. Finally, only limited space was available in the existing facility to house a new injector accelerator. These requirements dictated negative ion strip injection into a small synchrotron with single turn fast extraction and bucket-to-bucket kick injection into the Cooler. The injection and extraction energies (7 MeV H⁻ and 200 MeV P) were the minimum required to meet the intensity and resonance goals. The

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Table I: CIS Booster Design Parameters

Polarised Source	25 keV H⁻	25keV d⁻
Linac Pre-accelerator	7 MeV H⁻	4 MeV d⁻
Strip Injection Foil	4.5μgm/cm^2 C	3.0μgm/c^2 C
Fast Extraction	220 MeV P	105 MeV d
Extracted Intensity	$\geq 10^{10}$ p/pulse	$\geq 5 \times 10^9$ d/p
Rep. Rate	1 to 5 Hz	1 to 5 Hz

resulting design parameters for CIS are listed in Table I. With a budget of $3.5 M, only the Linac, RF cavity, and ring magnetic, diagnostic and extraction system were designed and fabricated specifically for CIS. The majority of the remaining systems (temporary H⁻ source, injection and extraction beam lines, ring vacuum system, etc) were assembled from surplus equipment available either in-house or from other laboratories (FNAL, AGNL, etc).

2 CIS CONFIGURATION

A schematic of the present IUCF nuclear research accelerator facilities, consisting of the new CIS booster synchrotron and the electron cooler storage ring, is shown in Fig. 1. A 25 keV H⁻ beam is matched to the acceptance of a commercial 7 MeV H⁻ linac pre-accelerator consisting of a 3 MeV RFQ coupled to a 4 MeV DTL [2,3]. Both operate at 425MHz. The 7 MeV H⁻ beam is strip injected into the synchrotron, protons are accumulated, RF captured, accelerated to 210 MeV and single turn fast extracted for bucket-to-bucket transfer
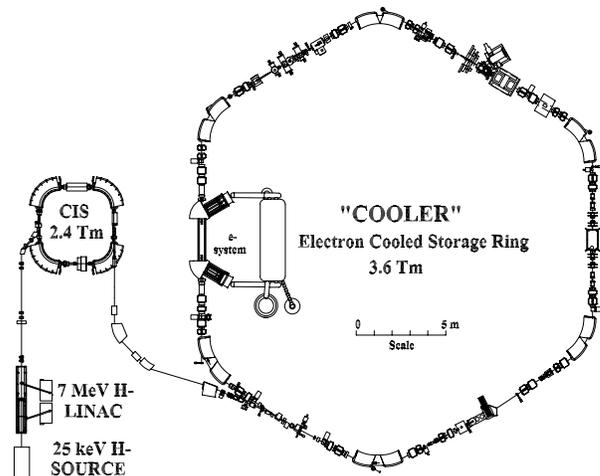
Figure1: Present IUCF Accelerator Research Facility

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into the Cooler ring for accumulation, electron cooling and further acceleration.

2.1 Polarised Ion Source

A high intensity polarised negative ion source (≥ 1 mA H⁻, d⁻ peak) with a colliding beam ionizer (CIPIOS) [4] was fabricated simultaneously with CIS, and was recently (3/99) installed in the CIS vault. Injection of polarised H⁻ beams from this new source, which is also capable of delivering polarised d⁻ ions, is scheduled to begin in June 1999. Deuteron beam pre-acceleration for CIS injection is done by replacing the 3 MeV H⁻ RFQ vanes with another set designed to accelerate q/A=1/2 ions to 4 MeV. The RFQ vacuum vessel and H⁻ vane assembly were fabricated with this replacement capability built in. The q/A=1/2 vane assembly is now being fabricated by AccSys Technology, Inc [5] with delivery scheduled for June 1999. Following initial installation and alignment of the new vanes (late 1999), switching from H⁻ to d⁻ operation will likely take 2 days. The CIS/Cooler H⁻ beam commissioning studies reported here were conducted using a surplus 0.5 mA (peak) unpolarized Duoplasotron source [6].

2.2 The CIS Lattice Design

A schematic of the CIS ring is shown in Fig. 2 and the lattice parameters are listed in Table II. CIS is a weak focusing synchrotron with optical properties determined by the ring dipole-straight length ratio and the dipole 12° edge angles. A quadrupole was installed in each straight to correct for dipole edge angle fabrication errors and to study ring performance at transition by making large tune changes. The lattice, linac pre-accelerator and major accelerator system hardware designs were previously reported [7,8,9]. Each of the four 2.34m long straight sections are filled with apparatus required for H⁻

Table II: Lattice Parameters for the CIS Ring

Circumference	17.364 m
Betatron Tunes; Qx, Qy	1.478, 0.72
Dipole Length	2.0 m
Dipole Edge Angle	12°
Dipole Bend radius	1.273 m
βx: Maximum	4.373 m
Minimum	0.996 m
βy: Maximum	3.786 m
Minimum	3.380 m
Dispersion: Maximum	1.759 m
Minimum	1.617 m
Chromaticity: Cx	-0.529
Cz	-0.156
Transition Energy	256 MeV
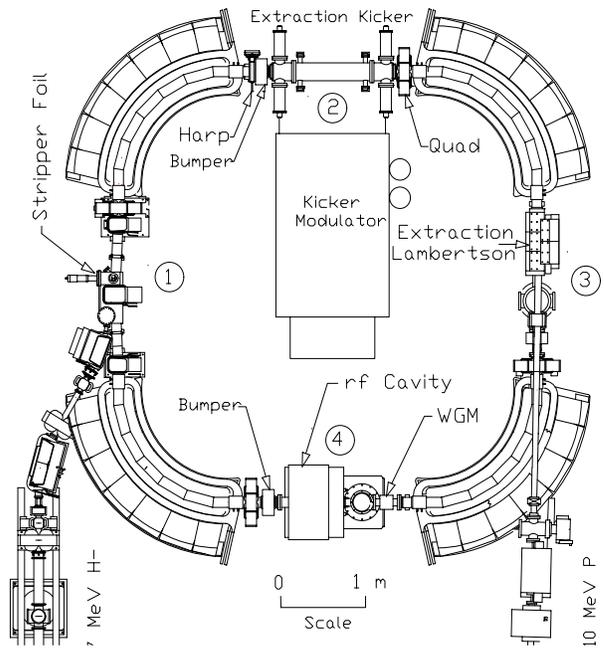
Figure 2: Plan view of the CIS 2.4 Tm Synchrotron Ring.

strip injection (1), single-turn kick extraction (2 & 3) and RF acceleration (4). Five vertical steering elements distributed around the ring and four main dipole trim coils are used for beam centering. Beam diagnostics consist of an x/y BPM pair placed at the entrance and exit of each dipole, a high bandwidth wall gap monitor, a ping tune kicker and a removable wire Harp to view circulating beam during injection [10].

2.3 Fabrication Challenges & Innovations

The energy and small circumference (1/5th Cooler) of CIS precipitated significant design and engineering challenges for the ring main dipoles and the fast extraction system. The ring design requires 90° laminated dipoles with a 1.273 m radius (37 cm sagitta) to ramp from 0.3 to 1.68 T at up to 5 Hz. 2-D and 3-D field calculations minimised multipole components in the C-shaped dipole [8], but a method to fabricate such small laminated 90° magnets was needed. The key to our design solution was the availability of 1.5mm thick modified 1006 sheet steel pre-coated with a B-stage epoxy resin (Remisol EB-540). A 4 to 6 micron thick layer of this resin, which serves as both the lamination insulation and bonding agent, is applied to each side of the sheet steel prior to stamping. The 90° magnet is fabricated from 5 wedge shaped and 2 end pack modules that are individually stacked, baked and precision machined to the required shape prior to mounting on a base plate assembly. The end pack pole ends are machined with a profile to minimise the magnet integrated sextupole component, which ensures a large dynamic aperture at fields up to 1.83 T. The magnet

DIPOLE PROPERTIES

Bend Angle:	90.0°
Bend Radius:	1.273 m
GAP:	58.0 mm
Edge Angle:	12.0°
Field Max:	1.83 T
Field Gradient:	0.0 T/m
1/1000 dB/B apt	50 x 100 mm
Turns/Mag:	24
Dynm. Pwr/mag:	705 kW
Weight/Mag:	38,000 lbs.
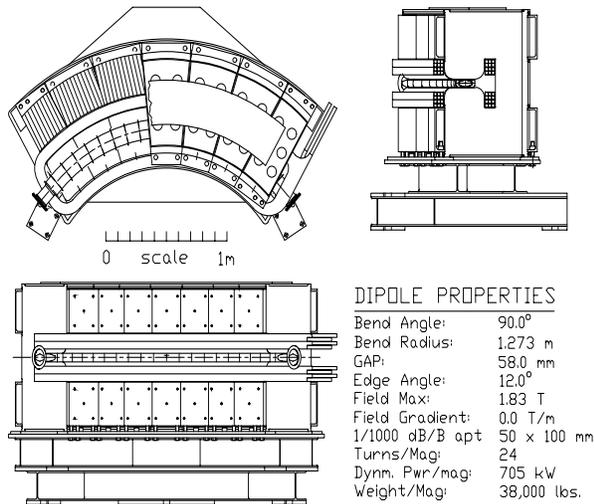
Figure 3: 3 view of a CIS main Dipole Assembly.

assembly is shown in Fig. 3 together with some measured field properties. The 1.5mm thick coated steel was also used to fabricate the remainder of the ring laminated magnets (2 rf cavity bias quads, 4 trim quads, and 5 ring vertical steering magnets). The steel was sheered to the required perimeter shape, stacked, and baked into blocks in-house and then sent out to be EDM machined to the desired pole tip shape, an economical solution for this small number of laminated magnets. The second challenge for this small ring is beam extraction. The orbit period for 200 MeV protons in CIS is 100 nsec. Hence, single turn kick extraction requires a fast kicker with $\leq$ 50nsec (10-90%) rise time to displace the beam across the 7mm thick septum of the Lambertson extraction dipole without loss [6]. A 1.3m long parallel plate, 50 Ω Blumlein kicker magnet [10] is installed in straight 2 (Fig. 2). A state-of-the-art pulse forming network and modulator were fabricated by Pulse Sciences, Inc. [11], which reliably delivers $\pm$ 55 kV, 300 nsec long pulses to the kicker with a rise time of about 35 nsec. 1.3m is the maximum space available anywhere in CIS, and the 55 kV plate voltage limit is imposed by reliability constraints on the pulse modulator thyratron tube, Application of $\pm$ 55 kV across the 4 cm kicker gap is calculated to displace a 200 MeV proton beam 20mm at the Lambertson septum entrance. This is enough for efficient extraction if the beam is bumped close to the septum prior to firing the kicker. The dipole trim coils are used to locally bump the beam away from the septum during acceleration and close to the septum for extraction. Kicker EMI during is negligible.

3 CIS BEAM COMMISSIONING

A 0.50 mA (peak) pulsed, 25 keV H⁻ beam from the duoplasmatron is focused at the entrance of the PL-7 linac. The H⁻ beam normalised emittance is 0.6 $\pi\mu$m,

smaller than the 1.0 μm acceptance of the RFQ. A double einsel lens focuses the beam (125mrad symmetric convergence cone) into the 2.5mm diameter RFQ entrance aperture. Beam transmission through the linac is nominally 80% and the normalised emittance and energy spread of the 7 MeV H⁻ beam are 1.0 $\pi\mu$m and 150 keV FWHM respectively, in good agreement with specifications.

The 425 MHz linac amplifiers have a 0.2% duty factor limit. The linac delivers a 200 μsec long, 300 μA (peak) 7 MeV H⁻ beam pulse at 4 Hz into a 9 m transfer beam line matched to the acceptance of CIS. Beam is strip injected on a 6mm x 25mm 4.5 μgm/cm^2 carbon foil. Two injection bumpers displace the circulating beam orbit 25mm onto the foil for coasting beam accumulation. The ring orbit period at injection is 0.48 μsec, hence the maximum theoretical peak intensity gain via strip accumulation is 400 (120 mA). Strip injection efficiency calculations [13] that account for phase space dilution effects of the foil predict an equilibrium gain of 120 (36 mA) after 200 μsec of accumulation. In practice, an intensity gain of 80 is routinely achieved after 175 μsec, corresponding to an initial coasting beam accumulation of 8 x 10^{10} protons. Part of the discrepancy between the calculated and measured gain is caused by the emittance growth of the circulating 7 MeV proton beam in the 0.1 μTorr average ring vacuum. Another source of beam loss at injection is the slow fall time (0.2 msec) of the bumper magnets after accumulation. Both effects can produce emittance growths nearly equal to that of the foil during injection. Vertical emittance growth during strip accumulation is the intensity limiting mechanism in CIS.

Optimal adiabatic capture of the accumulated beam requires a 2 msec ramp of the RF cavity to 250 V. The captured beam energy is 6.987 MeV. The fractional ring tunes are 0.48 horizontal and 0.72 vertical, in excellent agreement with the lattice predictions. The1/e lifetime varies from 0.22 seconds to an equilibrium 1.72 seconds in the 200 msec immediately following capture. Beam acceleration is initiated within a few μsec of RF capture, by which time lifetime losses reduce the stored beam to $\leq$ 2 x 10^{10} protons. This intensity is also consistent with the calculated 7 MeV circulating beam space charge limit of 5 x 10^{10} protons, although this has yet to be identified as a CIS intensity limit. Work is continuing to improve the ring vacuum and to reduce the injection bumper fall time to increase stored beam intensity.

3.1 CIS Acceleration Performance

Proton beam ramping development began at 50 MeV in November 1997, progressed to 225 MeV by December 1997, and culminated with the acceleration of 1.1x10^{10} protons to 240 MeV in April 1998. The ramp time (seconds), and n (ramp power) is an integer variable

from 1 to 5 which is used to vary dBρ/dt from 1.0 Tm/s (n= 5) to 8 Tm/s (n=1) for a 0.5 sec up-ramp to 200 MeV. The software calculates both the main dipole current and RF cavity frequency as a function of Bρ and creates a 96 vector ramp table for each. Beam acceleration is done open loop (no radial position feedback) via ramping the main dipole current and the accelerator cavity RF frequency. No other ring elements (dipole trims, quads, or steerers) are needed to achieve efficient, centered beam during ramping. 8 x/y BPM pairs and the high bandwidth Wall Gap Monitor (WGM) continuously monitor beam position and intensity around the ring during acceleration. The WGM also measures the circulating beam orbit period and bunching factor. Orbit centering errors are removed manually by making small modifications ($\leq 0.4\%$) to the RF cavity frequency ramp vector tables. A software program was recently implemented to read the horizontal BPM positions during acceleration and adjust the RF frequency vector table automatically. Two iterations of this program are enough to center the beam to ± 2 mm, a feature that reduces the setup time for new ramped energies to a matter of minutes.

To date, protons have been accelerated to energies from 50 to 240 MeV with ramp transmissions of 75% and flattop intensities over 1.1×10^{10} protons. All intensity losses occur during the first 200 msec of a 1-sec up-ramp and are also caused by gas scattering losses in the 0.1 μTorr ring vacuum. A beam phase feedback loop added to the RF acceleration system only marginally improves ramp transmission. The horizontal and vertical betatron tunes remain constant during acceleration at 1.485 ± 0.015 and 0.72 ± 0.015 respectively. The measured bunching factor varies from 3 at injection to about 5 at 225 MeV for RF accelerating voltages above 400 V. The 1/e lifetime of a 225 MeV proton beam in CIS is 573 sec.

The main dipole power supply has sufficient capacity to ramp protons to 250 MeV, although the magnets are already driven well into saturation (1.87 T) at 240 MeV. However, insufficient ac line capacity causes significant line "flicker" for ramps above 210 MeV at rep. rates faster than 1 Hz. While higher energy and faster rep. rate development is planned, 200 MeV at 1 Hz is an ideal beam for Cooler injection. A 0.8 Hz, 200 MeV proton ramp cycle consisting of a 0.5 sec up- and down-ramp, a 50 msec flattop for extraction and a 200 msec reset and fill period was developed for this purpose.

3.2 CIS Extraction Performance

The fast kicker and Lambertson septum extraction dipole present the smallest horizontal apertures, 4 cm and 5 cm respectively, to the CIS circulating beam. caused no intensity losses at injection when installed, but the Lambertson dipole requires a 7mm circulating beam local orbit bump away from the septum to
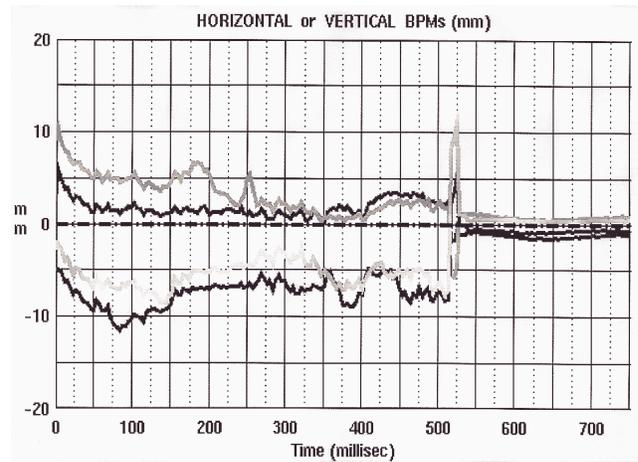
Figure 5: BPM scan for 0.5 ramp to 200 MeV protons.

maintain intensity during acceleration. This local bump is shown in Fig. 5, which is a BPM scan for a 0.5 sec ramp to 200 MeV. The kicker magnet is between dipoles 1 and 2, and the Lambertson entrance is just after the exit of dipole 2 (see Fig. 2). The beam positions at the entrance and exit of dipole 1 (top 2 traces) remain nearly centered during the ramp, while the positions in dipole 2 (bottom traces) are moved -7mm to the ring inside to prevent abrupt losses half way up the ramp. The Lambertson vacuum chamber apparently induces these losses, which were not observed prior to its installation. The local bump is inverted at the flattop just prior to extraction, when the beam exiting dipole 2 is bumped +17 mm to the septum edge. This can be seen in Fig. 5 beginning at 520 msec. Beam is extracted at 525 msec.

The Lambertson extraction channel horizontal width is 16mm. The diameter of a 10 πμm, 200 MeV proton beam is about 11mm, hence a careful alignment of the Lambertson dipole with the extraction orbit is required. Over 1×10^{10} protons have been extracted from CIS at 150, 200 and 210 MeV. Extraction efficiency is typically 75%, and has been as high as 86%. Fig. 6 is a display of the +55 kV extraction kicker pulse monitor (top), a WGM display of the last 4 orbits of the circulating beam at the flattop (middle), and a BPM

Figure 6: Kicker, WGM and BPM outputs for a 200 MeV extracted proton beam from CIS.

signal of the extracted beam in the Cooler transfer beam line (BL9A) for a 200 MeV proton beam. The horizontal scale is 100 nsec/Div. The rise time and width of the 55 kV kicker pulse are 35 and 300 nsec. The orbit period (WGM) of the 200 MeV flattop beam is 100 nsec, the FWHM bunch width is 21 nsec, and the bunch factor is 4.76. The BPM FWHM signal for the extracted beam is also 21 nsec, and measures 7×10^9 protons, 60% of the 1.1×10^{10} protons measured in CIS by the WGM. The extraction kicker for this run was at maximum voltage. In later runs, the kicker plate gap was reduced to 3.7 cm, and the extraction orbit bump was optimised to extract 1.1×10^{10} protons of 1.3×10^{10} at 200 MeV (85% extraction effic.) with a kicker voltage of ± 51 kV. While careful alignment of the extraction bump is required for this performance, experience has shown that the acceleration and extraction of beam from CIS is quite reproducable.

4 COOLER INJECTION

Approximately 9×10^9, 200 MeV protons/pulse at 0.8 Hz are routinely available from CIS for Cooler injection. A preliminary measurement of the normalised emittance in BL9A is about 18 $\pi\mu$m, and should be considered an upper limit. Transmission through BL9A to the Cooler injection system is $\geq 90\%$. The Cooler injection dipole apertures were recently modified to accept 10 $\pi\mu$m emittance beams and the Cooler injection ferrite kicker magnet rise time was reduced from 200 ns to 70 ns to reduce losses at injection. The single pulse injection efficiency of CIS extracted beam into a Cooler stored orbit is 50%, corresponding to 4×10^9 injected per CIS cycle. Reducing the CIS extracted beam emittance by optimising strip injection parameters may increase Cooler injection efficiency, but has yet to be attempted.

Two methods of CIS beam accumulation in the Cooler have been demonstrated. The first and easiest is coasting beam cooled accumulation where CIS beam is injected and cooled with no Cooler RF cavity voltage. Fig. 7 is a low bandwidth PCT display of this type of accumulation for 200 MeV protons in which beam is accumulated to over 2.4 mA (8×10^9 protons) in 8 sec, or 6 pulses from CIS. The vertical scale is 0.5 mA/Div.
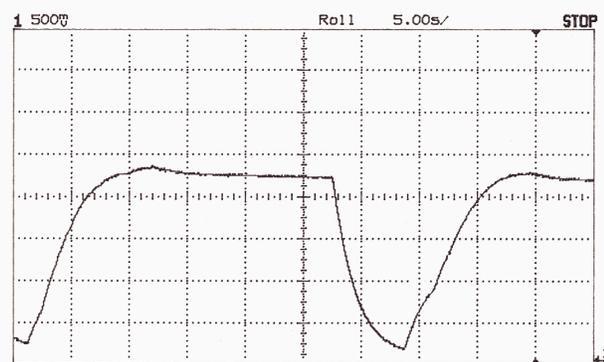
Figure 7: PCT display of 200 MeV proton accumulation

Beam also accumulates to nearly the same current via "sequential" cogging of 5 CIS pulses into the Cooler operating on the 5th harmonic. For this fill method, the timing of each extracted pulse from CIS is synched with the center of each Cooler RF bucket in sequence until all 5 buckets are filled. Beam centering and ramping was demonstrated in the Cooler using the new injection trajectory from CIS. The stored beam energy and 1/e lifetime in the Cooler are 201.57 MeV and 1100 sec. The momentum spread of the un-cooled beam injected into the Cooler is $\pm 0.2\%$, the Cooler design acceptance.

The present record of 3 mA accumulated in the Cooler with CIS injection is not yet limited by instabilities, but by the availability of development time. CIS/Cooler development competes with the polarised source installation work and Cooler experiment. Cooler experiments began with 200 MeV un-polarised protons from CIS in January 1999 with a significantly increased duty factor and stored beam intensity (1-2 mA average). The stability and reliability of Cooler stored beam is excellent, with intensities varying by less than 10% from cycle to cycle. Reproducibility is excellent throughout the system and turn-on and setup of the Cooler with CIS injection has been done in as little as 6 hours.

5 ACKNOWLEDGEMENTS

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