THE INDIANA COOLER INJECTOR SYNCHROTRON PROJECT

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CIS RING DESIGN:

In August of 1994, Indiana University and the NSF jointly funded ($1.5 and $2.0 M, respectively) the construction of a low-energy rapid-cycling synchrotron. The new Cooler Injector Synchrotron (CIS) is designed to inject high-intensity polarized protons and deuterons into the existing electron-cooled storage ring. The Cooler is presently filled with light ion beams (H^+ through $^4He^{++}$) of modest intensity from the IUCF cyclotrons. The strip injection and cooling accumulation of unpolarized $^2H^+$ ions have produced stored unpolarized beams up to 10^{10} particles in a few seconds. The more complex kick-injection and Cooling-accumulation technique for fully-stripped polarized protons and deuterons can yield 10^9 stored particles after several minutes. CIS is designed to fill the Cooler with a minimum of 10^{11} polarized protons or deuterons in a matter of seconds, while significantly reducing overhead and operating expenses incurred by the Cyclotron/Cooler beam-matching requirements. While stored polarized beams of a few 10^{10} will significantly enhance the developing spin-physics program on the Cooler, 10^{11} stored polarized ions will open new avenues of research, as well as provide excellent beams for filling a higher energy spin synchrotron, LISS.

The layout of the new injector and a table of relevant parameters are provided in Fig. 1 and Table I. Polarized H^- ions from HIPIOS at 25 keV are accelerated to 7 MeV with an RFQ/DTL combination (PL-7) operating at 425 MHz provided by AccSys Technologies. Negatively-charged deuterons are similarly accelerated to 6.0 MeV by a separate RFQ, which will also be capable of accelerating other ions with $q/A = 1/2$. A 2.5-m transmission beam line is used to both de-bunch and phase-space match these beams to the CIS injection requirements. Beam transmission from the source through the PL-7 is 85% for a beam having a normalized emittance of 1.0 π mm·mrad. Space-charge longitudinal emittance growth of the 7-MeV beam in this line is negligible for intensities below 200 μA, although the RFQ/DTL and beam line are designed for efficient transmission of 1 mA beams. The FWHM momentum spread of the beams from the RFQ is 0.5%.

Beam from the RFQ is strip-injected into the CIS ring via a DC magnet chicane and two bumper magnets located in adjacent straight sections to move the closed orbit onto the stripper foil. Following accumulation, the beam is adiabatically captured into a first harmonic RF bucket via a tuned, quad-biased RF cavity similar in design to the present Cooler MPI RF cavity, and then accelerated. The RF cavity voltage and beam position and phase feedback are used to confine the beam during the ramp. Single-turn beam extraction is accomplished using a fast rise-time (50 ns) horizontal counter-traveling-wave kicker which jumps the beam across the 5-mm septum of a vertical Lambertson magnet located 90° later in phase advance. An injection bumper and a dipole correction coil are also used to move the closed orbit near the septum edge prior to firing the kicker.

CIS is a weak-focussing synchrotron with a superperiod of 4 and operates below transition. Primary beam focussing is determined by the C-shaped corner dipole-edge angles.

TABLE 1. CIS RING PARAMETER LIST

I. Proton Beam Properties	INJ	EXTR
Maximum Design Energy (MeV)	7	200
Initial Operating Energy (MeV)	7	80
Momentum (MeV/c)	114.8	498.2
Rigidity (T·M)	0.383	1.03
Accumulated Emittance (π μm)	34.0	10.0
Orbit Period, 7-80 MeV (μs)	0.477	0.149
Tune Shift at 2.5×10^{10} part.	0.03	0.006

II. Lattice Parameters	
Circumference (m)	17.364
Straight-Section Length (m)	2.341
Dipole Magnet Radius (m)	1.273
Dipole Length (m)	2.0
Dipole Edge Angle	12°
Magnet Field Maximum (T)	1.68
Number of Quadrupoles	4
Hz Tune (Q_x)	1.463
Vt Tune (Q_y)	0.779
β_x (m): Max (mid-bend)	4.373
Min (mid-straight)	1.018
β_y (m): Max	3.786
Min (mid-straight)	3.387
Dispersion (m): Max (mid-bend)	1.759
Min	1.617
Momentum Compaction Factor	0.619
Chromaticity (x, y)	−0.53, −0.16

Four trim quads are provided for small tune adjustments. The ring magnet design is capable of accelerating protons to 220 MeV at 5 Hz. Protons will initially be limited to 80 MeV for routine Cooler injection to avoid an intrinsic depolarizing resonance at 108 MeV. Ring operation will also be limited to 1 Hz until a need for faster cycling rates is demonstrated. The CIS ring circumference (17.364 m) is 1/5th that of the Cooler to facilitate bucket-to-bucket transfer of beam into the Cooler. With the CIS ring cycling at 1 Hz, the Cooler, operating on the fifth harmonic of the orbit frequency, can be filled with 5 CIS pulses in 5 sec. Limiting CIS proton beam energy to 80 MeV also reduces the rise/fall time requirements ($\approx$70 ns) of the Cooler fast-injection kickers.

A critical performance area for the CIS ring is the intensity gain provided by stripping injection of relatively low intensity ($< 200\mu$A) polarized H^- beams available now. Strip injection without electron cooling induces energy spread, multiple scattering and dispersion-

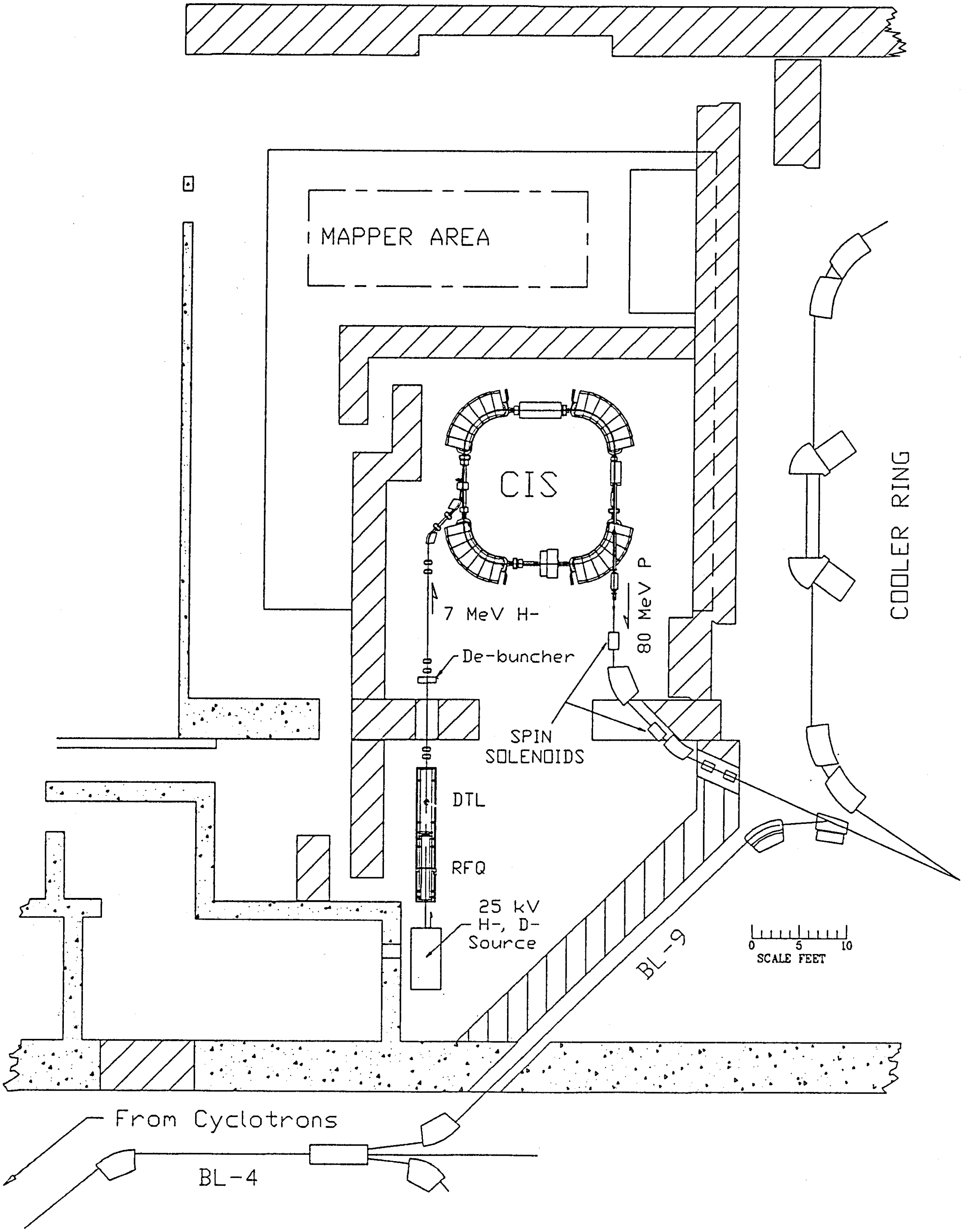

Figure 1. Layout of the CIS Ring next to the IUCF Cooler Vault.

coupled emittance growth losses during accumulation, which ultimately limit the intensity gain achieved. Incoming beam energy, intensity, emittance and energy spread, stripper foil thickness, ring dispersion and orbit distortion, and maximum permitted accumulated beam emittance are all factors determining the maximum number of particles injected into CIS. A fundamental limit for beams extracted from CIS is the acceptance of the Cooler, which is nominally 10.0 π mm·mrad. Detailed ray-trace computer simulations for the CIS ring and injection system, using a 7-MeV proton beam with a normalized emittance of 1.0 π and 90% energy spread of 1.0% on a 4 μg/cm^2 carbon stripper foil, predict a nominal intensity gain of 250. Consequently, a minimum H^- source intensity of 65 μA is required to achieve the design-intensity goal if transmission through the RFQ/DTL and through CIS are 85% and 60%, respectively. Accumulation time for this intensity gain is 230 μs, which matches well with typical beam pulse widths from polarized sources, and is within the range of the RFQ/DTL duty factor. The space-charge tune shift in CIS at injection is small (< 0.05) for stored beams below about 5×10^{10} particles. The IUCF Cooler ring has been using six-to-eight 4-μg/cm^2 carbon foils for several years now, and 4.5μg/cm^2 foils have been fabricated in our target laboratory.

PROJECT STATUS

The CIS ring lattice design has been finalized, although detailed beam-performance envelope calculations are continuing. Equipment hardware design and bid-specification packages for the major components (linac and dipole magnets) are complete and fabrication of these items has begun. The status of the various systems and components that make up the CIS ring is given below.

a) ION SOURCE DEVELOPMENT

An H^- Duoplasmatron test setup has been constructed and beam-commissioning studies are underway. This system will eventually be the H^- unpolarized source delivered to AccSys Technology for the RFQ/DTL acceptance tests, and also will be the source used for initial CIS commissioning. Pulsed 25-keV H^- beam intensities of over 200 μA into less than 1.0 π mm·mrad normalized emittance are required for injection into the linac. This source was assembled using mostly in-house spare parts. Design of the beam-transport system (LEBT) from the source to the RFQ entrance has begun. Delivery of the source and LEBT to AccSys Technology for the RFQ/DTL acceptance tests is scheduled to occur on January 9, 1996.

b) RFQ/DTL PRE-INJECTOR

A purchase agreement with AccSys Technology, Inc. to build the 7-MeV RFQ/DTL has been signed, and fabrication has begun. In this agreement, IUCF will supply several commercially-available items (power supplies and RF, vacuum and cooling equipment), and the stainless steel vacuum chamber for the RFQ. A vendor has been selected for the vacuum chamber, which is now under construction, and most of the commercially-available equipment required has been purchased.

c) 7-MeV INJECTION BEAM LINE

An initial design of the CIS injection beam line has been made, and the procurement of surplus quadrupoles and power supplies has begun. Eight suitable beam-line quadrupoles have been acquired from surplus and field-mapped at IUCF. IUCF also acquired the loan of an AccSys Technology, Inc. 4TW60 RF amplifier from Argonne National Laboratory. This is a 425-MHz, 80-kV amplifier needed for the debuncher in this beam line, and would cost us about $40,000 and significant RF group manpower to reproduce. It may also be possible to acquire several surplus power supplies from ANL, which now has a list of our CIS power-supply needs to see if there is a match between what they have and what we need.

d) DIPOLE MAGNETS AND COILS

The CIS Magnet Design Group has met weekly since the design-review meeting last February, and individual members have visited the BNL, FNAL and ANL magnet factories, plus several prospective vendors and fabricators. The CIS dipole magnet and coil designs are complete, and a bid package for their fabrication by an outside vendor has been sent out. Orders have been placed for the low-carbon magnet sheet steel, coating materials, and lamination stamping. 2-D Poisson calculations for the magnet cross section are complete, and 3-D calculations to finalize the pole-tip endpac shape and determine integrated multipole-field components are underway. These data will be used this summer to determine ring beam dynamics and field corrections required by this and the small radius of curvature of the dipoles. The CIS magnets are designed to operate at up to 1.69 T (200 MeV p) and ramp rates up to 5 Hz, although we expect to run below 1.2 T and at 1 Hz initially.

A study of the trade-offs between modified-linear vs. SCR supplies for these dipoles is in progress. The CIS dipole power supplies will be the biggest ever brought into IUCF, and bid packages for their fabrication are planned to go out August 1, 1995. This supply is required to be in-house and operational by Feb 1, 1996 to map the first dipole delivered from the fabricator.

e) RF CAVITY

Design of the CIS RF cavity, which is similar to the Cooler MPI first harmonic cavity, has progressed to the point where long lead-time items (the ferrite rings and low-level electronic components) have been ordered. The tuned, quad-biased RF cavity will operate over a frequency range of 1 to 10 MHz, at up to 500 V with about 1 kW of power.

f) CIS EXTRACTION

An "asymmetric" Lambertson magnet design, in which the low-field cavity in the pole tip is placed at an angle relative to the center of the pole-tip surface, is being studied. This configuration reduces the required pole area and is similar in design to ones made for CEBAF, and reported at the recent Dallas Particle Accelerator Conference. 2-D and 3-D Poisson studies of the vertical-extraction Lambertson magnet are underway. So far, the septum width is 5 mm, with less than 1 G integrated field in the low-field gap with 1.2 T in the pole region. End effects will also have to be reduced via these calculations.

Also, the Blumlein fast kicker is predicted to be practical (given present length and tube design) up to only about 180 MeV. While this is good for our initial operating plans, a good fast kicker design for 200-MeV protons needs to be found.

g) UTILITIES, FACILITIES AND SHIELDING

A new BL-9 shielding wall that separates the Cooler from the CIS construction area is complete. This job required the relocation of cable trays, water lines and He lines, in addition to actually building the wall. The cut in the poured concrete wall for the CIS extraction beam line was not done as planned during the shutdown because of complications with the wall structure, which is a load-bearing wall. Consequently, we are presently looking at alternative ways of getting the beam from CIS to the Cooler that will not violate the integrity of this wall. Removal of the offices in the Cooler-Tripler pit, which now occupy the space required by the CIS ring, will begin during late summer of 1995.

The existing Cooler substation has an extra capacity of about 1.0 MVA. For CIS, a total of 300 kVA is required for all systems except the main dipole power supply. In addition, an AC distribution system of 900 kVA already exists on the south end of the Cooler balcony. Hence, all that is required is to rework the existing AC distribution panel to meet the needs of CIS non-dipole AC power needs, and then to provide a separate AC power source for the main dipole power supply. This last piece can actually be built into the dipole power supply itself, and is currently being studied by John Budnick, as mentioned earlier. The cost of all AC utilities remains at the $100,000 budgeted. Some of this, however, may be directed to the main dipole power supply.

A quick review of the water-cooling requirements indicates that we must build a dedicated CIS water-pumping system with distribution pumps, heat exchanger, de-ionizer system and holding tank. We made such a system for the Cooler and the K600 in 1984. Based on the cost of this system, current cost, including inflation, will be about $100,000, or $40,000 more than initially budgeted.

BUDGET

The CIS construction budget was awarded to IUCF in August of 1994, and a design review of the CIS project was conducted in February of 1995. Since then, approximately 50% of the funds have been committed. The major expenditures were on the RFQ/DTL Linac ($1.1 M), and the main dipole magnet and coil fabrication. So far, the cost of items purchased for CIS are as planned, and the project remains on budget. A plot of CIS equipment expenditures as a function of month after contract approval is shown in Fig. 2.

CONSTRUCTION SCHEDULE

A complete PERT of the CIS construction project has been compiled and is presently being analyzed and modified to smooth out manpower requirements. Manpower overcommitments may require rescheduling of certain activities to match our manpower capabilities, and outside vendors may be sought for certain projects where budget and manpower constraints require. An engineering consultant from ANL has been contracted to give us an outside review of this PERT to locate problem areas and to recommend possible solutions. The project construction schedule calls for beam-commissioning studies to begin with the RFQ/DTL in mid 1996 using a duoplasmotron H^- source, and with the CIS ring in the first quarter of 1997.

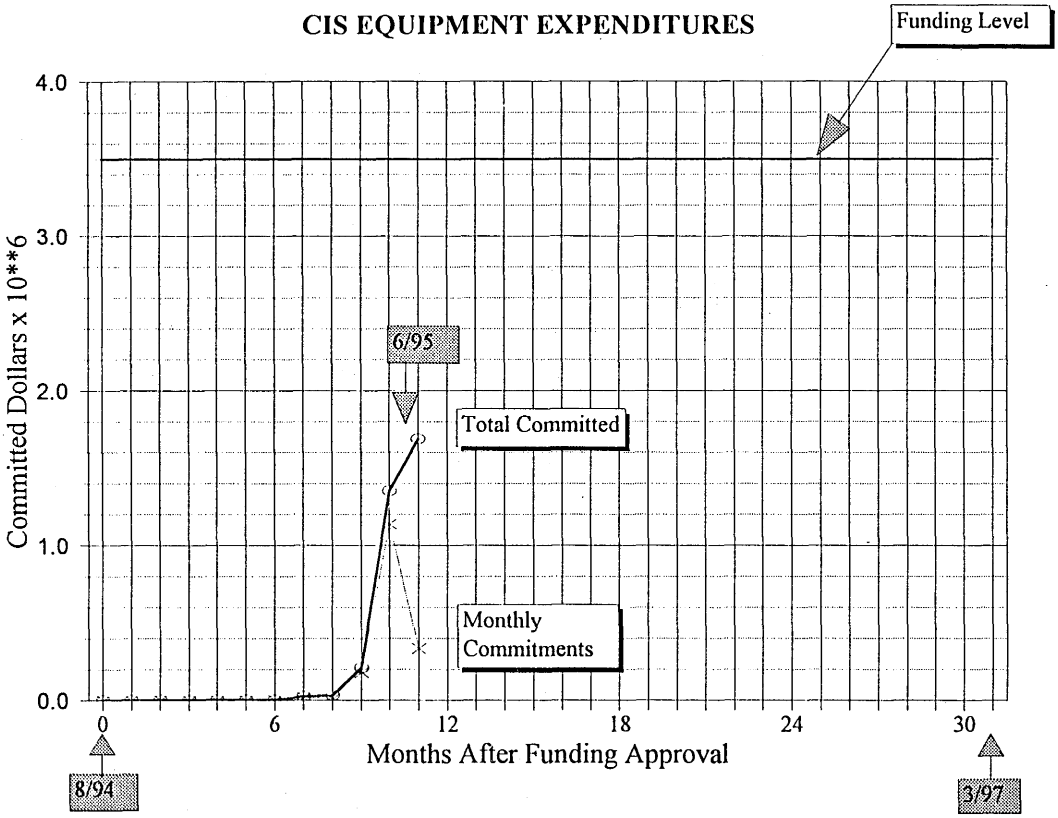

Figure 2. CIS Budget expenditure history.

THE LIGHT ION SPIN SYNCHROTRON (LISS) PROJECT

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I. *The LISS Accelerator Complex*

The principal design goals for LISS are: (1) to accelerate 0.4 GeV polarized protons from the IUCF Cooler ring to maximum energies within the range 10–20 GeV, and other fully-stripped light ions ($A \leq 40$) to corresponding energies (scaled by the charge-to-mass ratio); (2) to accumulate up to $\sim 10^{12}$ particles (corresponding to a circulating current of ~ 0.1A) and store beams for times of order 10^4 s in the absence of internal targets; and (3) to allow for in-ring experiments with internal targets at several long, magnet-free straight sections.