THE INDIANA COOLER INJECTOR SYNCHROTRON 1995-96 STATUS REPORT

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INTRODUCTION

Construction of a dedicated 2.24-T·m, rapid-cycling booster synchrotron (CIS) to inject high intensity polarized-proton and deuteron beams into the IUCF electron-cooled storage ring is now in its 23rd month. A plan view of the booster ring and linac injection system is provided in Fig. 1, and the ring design parameters are given in Table I. Further design details are given in several previous reports.[1,2] For initial ring commissioning in 1997, unpolarized H^- ions at 25 keV will be pre-accelerated to 7 MeV via an RFQ/DTL Linac, strip-injected into the ring, accelerated to $\leq$ 220 MeV, and single turn extracted for bucket-to-bucket transfer into the Cooler ring at 1 Hz. The project has progressed this year from a design/engineering to an equipment fabrication, installation and development effort. An extended accelerator shutdown (8 weeks) beginning April 8, 1996, was dedicated to final preparation of the CIS accelerator vault and the installation of all CIS-related utilities (AC power, water, air and cable distribution systems). The 7-MeV H^- beam-injection hardware, which includes the 25-keV H^- source, LEBT, and a 10-m injection beam line, was also installed during this shutdown. The present status and projected completion schedule of the various accelerator systems are outlined in this report, which is a summary of the dedicated and enthusiastic efforts of nearly all the technical staff of the IUCF.

INJECTION

a) Ion Source and LEBT

A 25-keV H^- source test stand, assembled from in-house spare parts, produced a DC 130-μA H^- beam with a measured normalized emittance (ϵ_n of 0.25 πmm-mrad) for continuous running periods exceeding one week. A pulsed H^- beam (300 μsec at 1 Hz) with a peak intensity of 270 μA was also developed. These measurements were used in the optics program "TRAK" to design a 25-keV transport system (LEBT) to inject beam into the RFQ accelerating structure. Beam properties required at the RFQ entrance are: $\epsilon_n \leq 1.0$ πmm-mrad, symmetrical convergence half-angle and beam radius of 125 mrad and $\leq$1.3 mm, respectively. A production 25-keV H^- source and LEBT were then assembled in the CIS vault during the April 1996 shutdown. This system, shown in Fig. 2, consists of the Duoplasmatron source, two diagnostic "crosses", and a double Einsel-lens system mounted directly on the RFQ entrance flange to produce the required convergence and focus. Provisions are made for beam steering and electron suppression, while the diagnostic crosses house beam-current and emittance-measurement devices. A multi-wire harp,[3] similar to an FNAL design, was developed for inclusion here and elsewhere in the CIS accelerator system. Presently, a pulsed H^- beam of 0.5 mA peak intensity has been

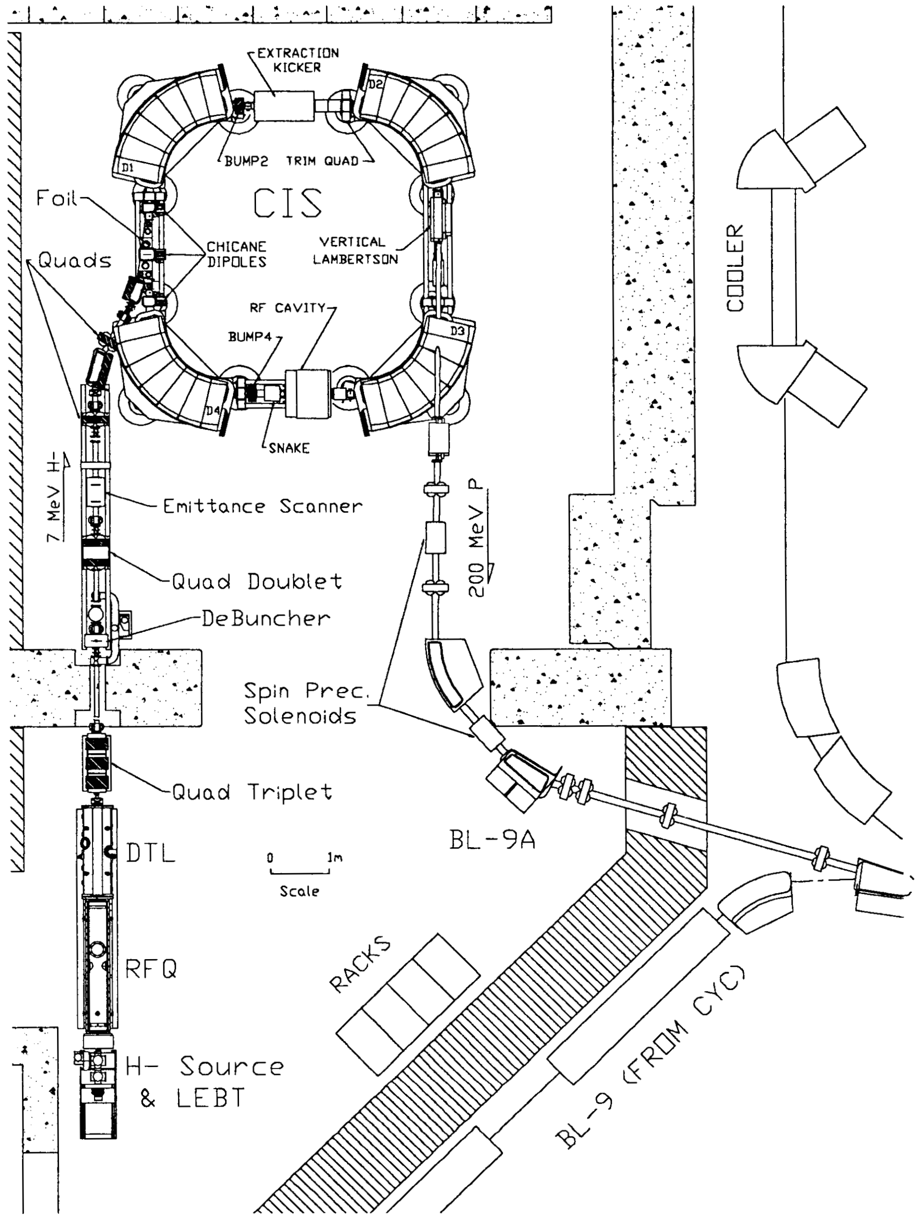

Figure 1. CIS Ring and Injection layout.

focused to less than 2-mm diameter approximately 18 cm downstream from the final lens. Beam emittance and convergence measurements are continuing.

b) RFQ/DTL Pre-Injector

Since signing a purchase agreement with AccSys Technology, Inc. to build a 7-MeV H^- Linac in June, 1995, fabrication has proceeded more slowly than hoped. IUCF has delivered all equipment required by the agreement, including the stainless steel RFQ vacuum enclosure, vacuum pumping hardware and PLC controls, and RF equipment. The PL-7

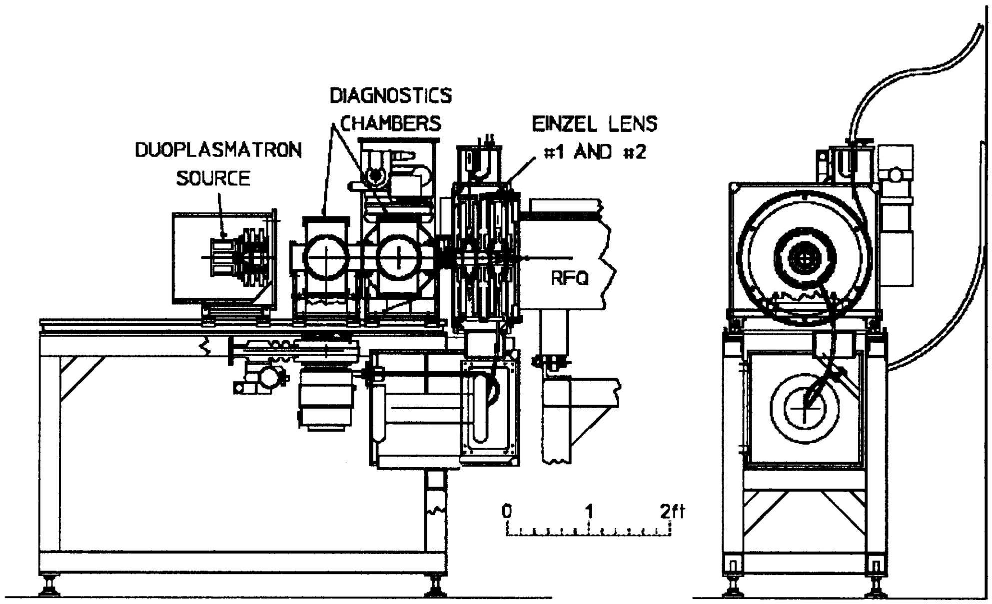

Figure 2. Unpolarized H^- Source and LEBT.

Linac assembly, a 3-MeV RFQ coupled to a 4-MeV DTL (Drift Tube Linac), has been assembled, tuned and vacuum tested (to 10^{-7} Torr) at the Accsys Facility. Fabrication of the three stage 360-kW, 425-MHz power amplifiers is nearly complete and subsystem debugging is in progress. Several IUCF technicians spent a total of 4 manweeks at Accsys to learn about the accelerator and assist in its assembly. The most recent vendor schedule calls for the system performance testing at AccSys in early September, 1996. Following satisfactory completion of these tests, the Linac will be delivered to IUCF and immediately installed in the CIS vault. The 25-keV H^- source, LEBT and 7-MeV transmission beam line are already in place, and will be used for the final Linac acceptance tests during the fall of 1996.

c) 7 MeV Injection Beam Line

The optical and mechanical design, fabrication and installation of the 9.8-m transfer beam line from the Linac to the CIS ring are complete. The beam line is used to de-bunch and phase-space match the 7-MeV H^- beam to the CIS ring Twiss parameters at the stripper foil. A quad triplet immediately following the Linac exit produces a double waist at a 15-mm diameter debuncher aperture located 2.7 m downstream. The beam-line tune is variable from a match of the ring Twiss parameters to a double waist ($\approx$ 4-mm dia.) at the stripper foil. The debuncher rotates the 425-MHz bunched Linac beam 90° in energy-phase space, thereby reducing its momentum spread by a factor of 4 and improving the strip injection efficiency in the ring. All seven beam-line quads were acquired on surplus, mapped, installed and aligned on their supports. The 31° and 20° injection dipoles, coils and vacuum enclosure were fabricated in-house, assembled and mapped. The 31° dipole

Table I. CIS BOOSTER PARAMETERS

	Injection P	**Extraction** P
I. BEAM PERFORMANCE SPECS:		
T Initial Design (MeV)	7.0	216.0
Momentum (MeV/c)	114.8	644.45
Rigidity (T·m)	0.383	2.24
Beta (v/c)	0.121	0.582
Gamma (E/E_0)	1.008	1.213
Maximum Accum. Emitt. (μm)	34.0 π	10.0 π
Dynamic Aperture (Vt,Hz mm)	550×250	380×130
Orbit Period (μsec)	0.477	0.0994
Rev. Frequency (MHz)	2.097	10.056
Bunch Factor	2.0	2.0
ΔQ at 2.5×10^{10} part.	0.03	0.006
Avg. $I_{circ.}$ at 2.5×10^{10} (mA)	6.0	27.0

II. LATTICE PARAMETERS FOR 1/5 CLR:

Circumference (m)	17.364 (1/5th Cooler Circumference)
Straight Section Length (m)	2.341
Dipole Magnet Radius (m)	1.273
Dipole Length (m)	2.0
Dipole Edge Angle	12°
Magnetic Field Max. (T)	1.68
Magnet Gradient	0
5×10^{-4} dB/B Aperture (Vt,Hz mm)	50 × 90
Hz Tune (Q_x)	1.463
Vt Tune (Q_y)	0.779
β_X: Maximum (Mid-B)	4.373
Minimum (Mid-L)	1.018
β_Y: Maximum (Dip Entr/Exit)	3.786
Minimum (Mid-L)	3.387
Dispersion: Maximum (Mid-B)	1.759
Minimum	1.617
Mom. Compaction Factor	0.619
Chromaticity (x/y)	$-0.53/-0.16$
Transition Gamma (Energy (MeV))	1.271 (254)

has been installed, and will be used to verify the accuracy of the beam TOF energy-measurement diagnostics during Linac commissioning. The 3.7° and 7.4° chicane dipole and coil fabrication (also in-house) is complete, and mapping is in progress. These and the 20° injection septum dipole will be installed during a second scheduled CIS accelerator shutdown this December, after the installation of the CIS ring dipoles. Fabrication and installation of the beam-line steerers is also complete.

The surplus (AGNL) 4TW60, 60-kW, 425-MHz debuncher amplifier was successfully tested at full power into a dummy load. The cavity design is complete and procurement of a Cu plug suitable for in-house fabrication is in progress. The debuncher will not be available for initial commissioning of the Linac and beam line, but is scheduled for completion before the start of ring commissioning in March, 1997. All power supplies, diagnostic systems (BPM's, HARP, Stops, Viewers and TOF) and control DAC and ADC hardware are installed, and testing is in progress. Finally, the beam-line vacuum-pumping and PLC-control systems are installed and the beam line has been pumped down to the low 10^{-6} Torr range, suitable for initial beam commissioning.

d) Strip Injection System

The 7-MeV H^- beam is strip-injected into CIS via a DC magnet chicane and two bumper magnets located in adjacent straight sections as shown in Fig. 3. The H^- beam is converted to protons by a 4.5 mg/cm^2 thick, 7 mm $\times$ 22 mm Carbon foil strip, examples of which are fabricated and available in the IUCF target laboratory. Ray trace calculations predict an intensity gain of 250 for a 7-MeV H^- beam incident on this foil. Hence, the demonstrated 300-μsec H^- pulse with a peak intensity of 270 μA contains about 6 $\times$ 10^{11} protons. A transmission of 5% through the CIS ring is the minimum required to reach the design goal of 2.5 $\times$ 10^{10} particles per pulse extracted.

The design of the injection bumpers and power supplies, which are similar to ones used in the Cooler ring, is complete, and the dipole cores and excitation coils are fabricated. Mechanical designs for the injection straight vacuum enclosure, vertical ring steerers and multiple foil holder ladder mechanism, including diagnostic systems to reproducibly tune the beam to the ring closed orbit, are nearing completion.

COOLER INJECTOR SYNCHROTRON

a) CIS Lattice

CIS is a weak focussing synchrotron with a superperiod of 4 and operates below transition. A plan view of the ring configured for initial injection and acceleration tests is provided in Fig. 3. Primary beam focussing is determined by the C-shaped corner-dipole edge angles. Four trim quads permit small tune adjustments during routine operations and will also be used for advanced accelerator design studies near transition (256 MeV). The ring magnets and power supply designs are capable of accelerating protons to 220 MeV at 1 Hz. The lattice design is finalized, and detailed beam-performance envelope calculations are complete. Ring dynamic-aperture calculations by visiting scientist Yiton Yan from SLAC, using his program "DESPOT" to track particles through the CIS lattice, predict a dynamic aperture significantly larger than design vacuum enclosures throughout the synchrotron energy range, independent of the circulating beam momentum spread.

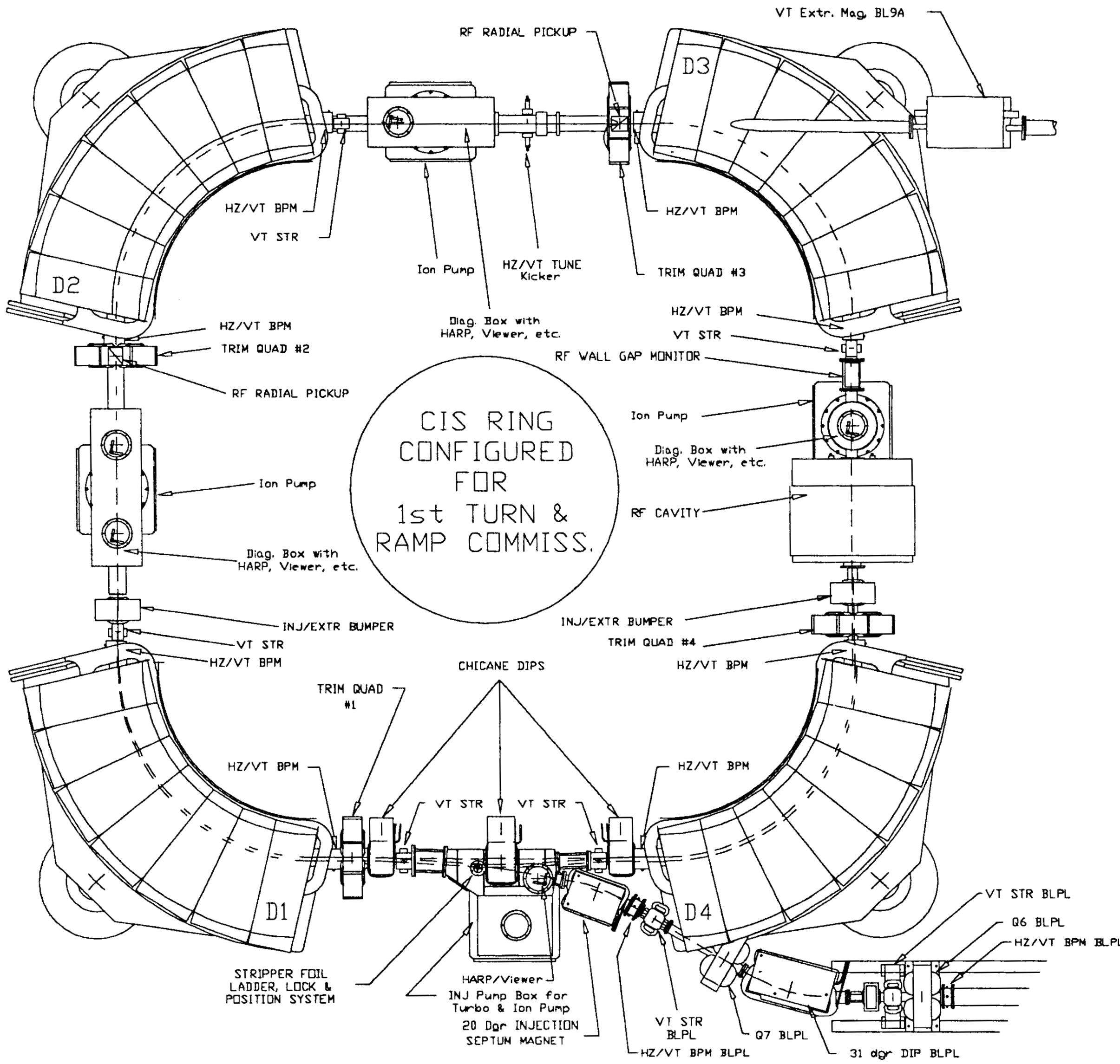

Figure 3. CIS Ring and Injection commissioning layout with extraction elements replaced with diagnostics.

b) Dipole Magnets & Power Supply

The CIS main dipole mechanical design was completed on June 9, 1995. On August 7, 184,000 lbs of Remisol EB-540 B-Stage epoxy-coated 0.059"-thick low-carbon sheet steel were delivered for dipole-lamination stamping, and between December 15, 1995 and January 18, 1996, 8260 stamped laminations (enough for nearly 5 dipole cores) were shipped to Elma Engineering in Palo Alto, California for final fabrication. IUCF took delivery of the first ring dipole from Elma on May 5, 1996. Field mapping of this dipole was completed using an in-house non-ramping 4000-A linear supply. Last minute compensation of this supply for the dipole-coil load was required, which delayed the start of mapping by several weeks. This, together with the late delivery (2 months) of the dipole from Elma, caused this work to be completed three months later than planned. Nevertheless, fabrication of the modified endpacks for the first dipole and the remaining three dipoles is proceeding at Elma Engineering, and all dipoles are scheduled to be delivered to IUCF before the end of November, 1996.

The field-mapping results agree well with the 2-D and 3-D Poisson calculations made during the design effort, and verify that field uniformity ($\Delta B/B$) over 90% of the required magnet aperture (100 mm Hz $\times$ 50 mm Vt) is $\leq 5 \times 10^{-4}$ at 1.68 T. The measured integrated sextupole component after several minor iterations of the pole tip endpack shape varies from 0.05 m^{-3} at 0.38 T to -0.2 m^{-3} at 1.78 T. Subsequent dynamic-aperture calculations from the measured field data agree with the theoretical calculations of Yan discussed earlier. The dipole entrance and exit angle is $12° \pm 0.1°$ over the same field excitation range. The dipole coils were found to be capable of continuous DC operation at 4000 A without overheating.

The rampable main dipole power supply, with a dynamic power of 2.3 MW, was acquired on surplus from FNAL in January, 1996, and is being installed in the CIS vault now. The FNAL equipment included a 13.8-kV transformer, which was installed together with newly acquired 12-kV switch gear on an electrically isolated and protected concrete pad outside the southwest corner of the Cooler building. The 12-kV AC power line to the transformer was installed by Public Service Indiana after the CIS April shutdown. The low voltage AC transmission line from the transformer to the SCR cabinet in the CIS vault was then installed to IUCF technicians. The SCR cabinet was assembled and tested, also with the help of IUCF technicians, at FNAL prior to delivery at IUCF. Compensation equipment (chokes and capacitors) were purchased and are being installed as they arrive. Work is progressing toward full ramp tests of this supply using one main dipole before the end of 1996. In addition, each dipole is equipped with back leg windings to allow up to 1% field adjustments for beam-centering purposes. The trim coils require ± 20 A at 200 V, and are similar to trim supplies now being acquired by FNAL for their new main ring injector. Hence, we have ordered these supplies from their suppliers.

c) Quads and Steerers

Fabrication of the 14 T/m, 5"-long trim quad iron cores and excitation coils is complete, and one of the four quads was assembled and mapped in April. The laminated trim quad cores were fabricated from the same epoxy-coated 0.059"-thick sheet steel used for the dipoles. Two 6000-pound rolls of this coated steel were sheered into 28″ × 36″ rectangular laminations and delivered to IUCF. They were further sheered to roughly the outer quad core shapes, stacked and baked into laminated blocks in-house. These cores were shipped to a commercial shop to be EDM machined to the precise quad profiles. The trim quad coils were produced using the IUCF coil-winding facility. Bid specifications for four rampable quad power supplies were used to select a suitable vender (P.I.E., Inc.), who is scheduled to deliver the completed units to IUCF before the end of 1996.

A prototype steerer core for the ring and for the 7-MeV H^- transfer beam line was fabricated and mapped. The ring uses 5 vertical steerers while horizontal steering is controlled by the 3 chicane and 4 dipole trim backleg windings. The final coil design for the steerers is complete and 23±10-A, 20-V power supplies are on-hand for this and other beam-line-steerer and dipole-trim purposes.

d) RF Cavity

The design of the CIS RF cavity and amplifiers is complete, and is discussed in a separate report.[4,5] The ferrite-tuned, quad-biased RF cavity has a frequency range of 1 to 10 MHz at up to 500 V with about 1 kW of power, and is capable of operation at 5 Hz. 2-D Poisson calculations were used to minimize transverse field components in the ferrite rings of the bias quad. The bias quad was fabricated in the same manner as the trim quads above, and is excited with a ±20-A, 20-V supply. Fabrication of the bias quad and all hardware required for assembly of the cavity is complete. Assembly of the cavity, while not a critical path item, is proceeding. All long lead time items (VCXO, ferrite rings, ceramic pipe, low level electronic components) are in-house. Present PERT projections call for commissioning of the RF system off-line in October, 1996.

Detailed discussions of the controls hardware and software designs for ramping resulted in beam-timing and controls-hardware specifications. Methods for software interfaces to the user, modifying and optimizing ramp transmission and diagnosing ramp transmission problems were studied at the BNL AGS Booster facility last spring. Closed orbit errors during ramps are suppressed using beam radial position feedback to the RF frequency, provided by two radial BPMs located half-a-betatron period apart in the ring. Beam-phase feedback is employed during ramping to damp beam-phase oscillations and reduce emittance growth.

CIS EXTRACTION

a) Single Turn Fast Extraction

Single turn fast extraction from CIS may be the biggest technical challenge of this ring design. The ring equilibrium orbit following acceleration is moved close to the septum of vertical Lambertson magnet using the injection bumpers and two corner dipole trim windings. A counter-traveling wave (Blumlein) kicker located 90° in phase advance upstream produces a 17-mrad kick to displace the beam across the septum, where it is deflected 12° vertically out of the ring. The orbit period for a circulating 200-MeV proton is 104 ns, which sets the kicker risetime requirement at $\leq$50 ns for a beam bunching factor of 2.0. Conceptual design of a 1.36-m long fast kicker with a plate gap of 4 cm, based on an operating LANL design, predicts a kicker voltage of ±60 kV, which is the realistic maximum operating voltage for the CX-2025X thyrotron tube. The kicker length is constrained to be $\leq$1.5 m by the demands of other required elements in the 2.43-m long straight section. One can optimize the trade-offs between deflection angle and gap reduction to achieve the required kicker voltage to maximize extraction efficiency and minimize the ring aperture reduction. It is clear, however, that designing a kicker with a plate voltage >60 kV is not practical. The final design of this kicker will have to resolve these trade-offs, and Poisson calculations to optimize the kicker-plate profile are just now getting started. Meanwhile, bids have been let for the fabrication of the kicker power-supply-charging and trigger circuits by a commercial vendor.

The magnetic design of an asymmetric vertical Lambertson magnet is complete. 2-D and 3-D Poisson studies of this magnet were made which predict an integrated low field of about 10^{-4} T with a gap field of 1.2 T. The Lambertson field required to produce the 0.22 rad deflection for a 200-MeV proton beam is about 0.9 T. Beams deflected by this magnet pass through a portion of the corner dipole endpack yoke and are bent back to the horizontal plane by a sister magnet with a simplified return yoke. Both dipoles are powered in series using an existing in-house supply. The mechanical design for these dipoles is nearly complete and the dipole coils have already been fabricated in-house.

b) Extraction Beamline (BL9A)

Beam extracted from CIS and passing through the vertical Lambertson magnet pair will be at the Cooler-injection beam-line height. Beam is then directed through two horizontal dipoles (42° and 32°) required to circumnavigate a structural wall separating the CIS and Cooler vaults and directed into the last dipole of the existing beam line (BM-4, BL9) from the Cyclotrons to the Cooler. From this point, the Cooler injection beam line is unchanged from the present design for the injection of CIS beams. Preliminary optics calculations using the program "SYNCH" indicate a need for 6 quads and the 2 dipoles. Provision to orient particle spin arbitrarily as required for experiments in the Cooler is accomplished by the insertion of a 1.6-T solenoid before and after the first 42° bend magnet in the beam line. While acquisition of the solenoids is not part of this project, IUCF now has the ability to fabricate them in-house. More detailed optics calculations, using "TRANSPORT" and "TRACE-3D" with realistic magnetic elements are proceeding now.

The quads for BL9A will be a combination of available in-house cyclotron high energy beam-line quads, and surplus quads. We are seeking 8 surplus 2"-aperture, 22-T/m quads along with several vacuum pumps and gate valves for use in this beam line from the BEVALAC. While the quad aperture is somewhat small, there are several places where they are well suited for this transmission line. The current and voltage requirements are the same as for the Cyclotron HE quads, and will be powered by load switching with the quads in BL9 from the Cyclotrons. Spare 42° and 32° dipoles, identical to those in the Cyclotron-Cooler beam line, exist in-house, and will similarly be powered by load switching of existing power supplies. The beam-line support structures are identical to those in BL9, and will be fabricated in the machine shop as priorities allow.

c) Cooler Injection

Single turn bucket-to-bucket transfer of beam into the Cooler is accomplished using a single Blumlein kicker located just upstream of the corner-one dipole pair following the Cooler-injection straight section. Beam is injected into the Cooler through the strip-injection path in L91 and the Lambertson magnet DIA (the larger of the two Lambertson apertures in this magnet) in the injection straight section. The requirements for this kicker are nearly the same as for the CIS extraction kicker ($\leq$50 ns risetime, $\leq$17 mrad deflection), but the falltime must be less than 100 ns to fill all five Cooler buckets with CIS beam. The design of this kicker will be done in parallel with the extraction-kicker design late in 1996.

BUDGET

Of the \$3.5 M awarded to IUCF for the construction of CIS, \$2.9 M (83%) are committed after 23 months of the 30 month construction program. A plot of CIS equipment expenditures as a function of month after contract approval is shown in Fig. 4. The major budget items (main dipoles, dipole power supply, Linac, etc.) were procurred at or below projected costs, partly because of the fortuitous acquisition of expensive surplus accelerator hardware from the major national accelerator laboratories (ANL, FNAL). This has led to an increase in the Linac and ring-extraction energies for protons from 3 to 7 MeV and 80 to 200 MeV, respectively, which significantly enhances the overall performance of the booster as an injector for the Cooler. Consequently, operation of CIS at 200 MeV for protons at 1 Hz will be accomplished within the original budget of \$3.3 M, with a contingency of \$0.2 M. The largest budget items for 1995-6 were the RFQ/DTL Linac (\$1.1 M), and the main dipole magnet and coil fabrication (\$0.47 M). No major purchases are required to complete the CIS ring project other than the radiation-shielding wall blocks and roof beams and the Blumlein kickers.

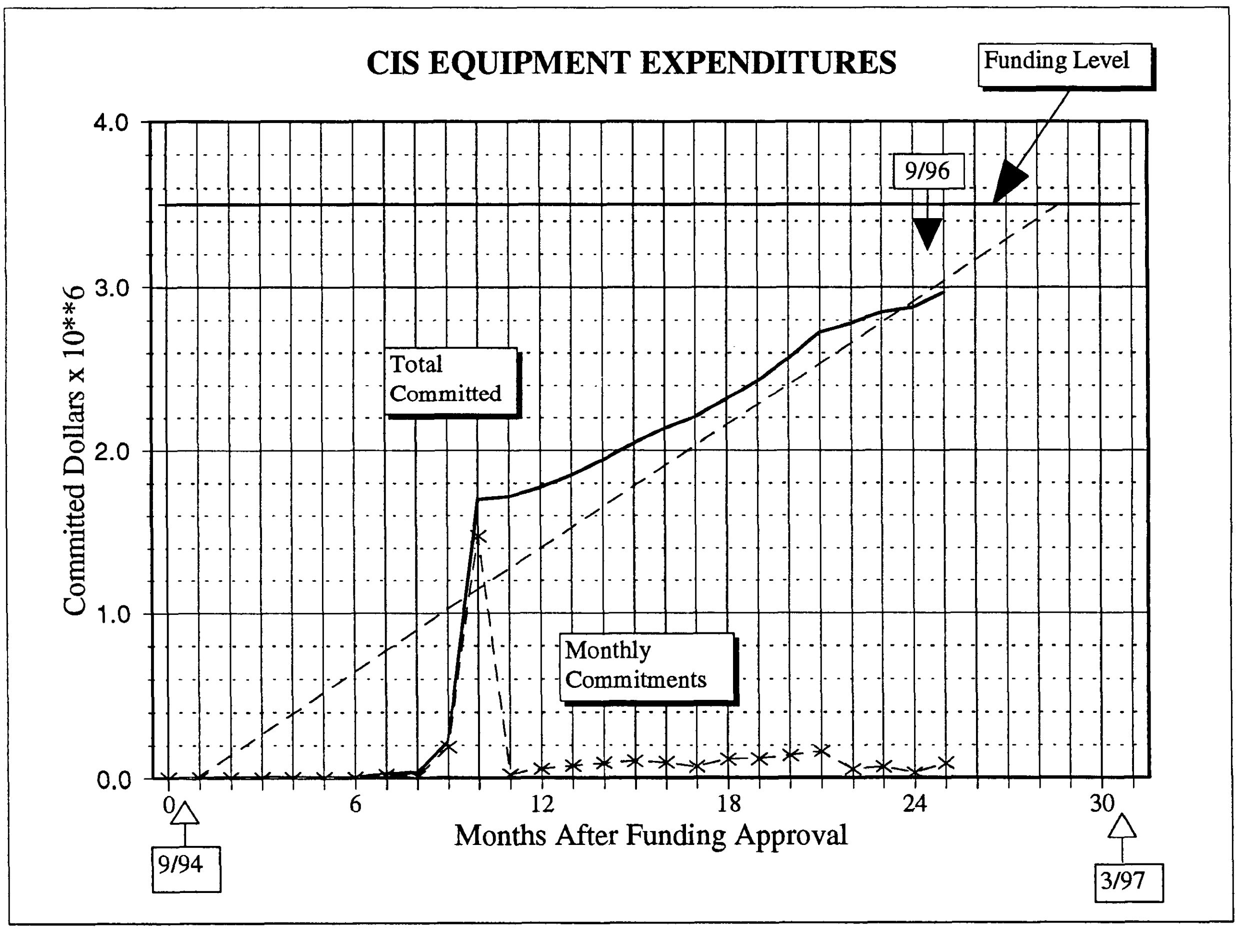

Figure 4. Budget history of the CIS project.

CONSTRUCTION SCHEDULE

CIS construction priorities are governed via a series of PERT schedules for all major hardware systems, and a final assembly schedule which project the start of ring commissioning by the end of March, 1997. Manpower requirements of the individual PERTs are combined into a single projection used to forecast manpower needs of the whole project. Space precludes the inclusion of the PERT output in this report, although scheduling details for the fabrication of the various major systems are included in the discussions of those systems above. It has always been recognized that IUCF does not have the personnel available in-house to meet this demanding schedule. Accordingly, the PERT projections show manpower deficits in several areas throughout 1996. Some of this deficit was removed by the acquisition of surplus equipment from several national laboratories, by designing equipment to be fabricated at commercial facilities, and by the use of professional consultants and hourly employees at IUCF. At present, the construction schedule is still on track for meeting the March 1997 schedule for the start of ring commissioning, even though a few of the in-house activities and the delivery of the linac have slipped by three months. On the other hand, delivery of the four ring dipoles, the small injection dipoles and ring quads is on schedule. The first prototype dipole mapping is complete, and the delivery of the remaining three dipoles is promised by the end of November, 1996. Linac and BLPL beam commissioning can begin in September, and final ring assembly will begin in December, 1996. The challenge to IUCF will be to complete the many small fabrication and installation tasks needed to complete the ring following installation of the dipoles. The work completed during the next few months is critical to meeting this goal.

1. D.L. Friesel *et al.,* in *Proc. of 1995 Particle Accel. Conf.,* Dallas, TX, (May 1-5, 1995) p. 357.
2. D. Li *et al.,* in *Proc. of 1995 Particle Accel. Conf.*, Dallas, TX, (May 1-5, 1995) p. 357.
3. M. Ball and B. Hamilton, in *Proc. of the 1996 Beam Inst. Workshop*, AGNL, (May 6-9, 1996) to be published.
4. A. Pei *et al.,* in *Proc. of 1995 Particle Accel. Conf.,* Dallas, TX, (May 1-5, 1995) p. 1705.
5. A. Pei *et al.,* in *Proc. of 1995 Particle Accel. Conf.,* Dallas, TX, (May 1-5, 1995) p. 1708.

H^- POLARIZED ION SOURCE FOR CIS

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A Technical Advisory Committee (TAC) met at IUCF in February 1996 to consider which available polarized ion source options would meet the requirements of CIS, would minimize the cost for a given performance, and would result in a reasonable schedule for