A. THE IUCF COOLER PROJECT

Introduction - R.E Pollock

The IUCF Cooler is a 3.6 Tm storage ring with electron cooling, designed to be injected with beams from the IUCF cyclotrons, and to permit the use of stored, cooled beams for internal target experiments in nuclear science at intermediate energies. The project was proposed at the end of 1980, was funded for construction in 1983, and is expected to come into first operation in 1987, so that the year 1986 covered by this report is near the end of the construction phase.

One of the highlights of the past year was the delivery, mapping, installation, and first operation in ramping (for synchrotron acceleration) mode of the twelve main ring dipoles.

The ring quadrupoles, as this is written, are in full production, being assembled and mapped in batches of five every two weeks, and are being installed in the ring, with a rate of one pair/week to continue through the spring until all eighteen pairs are in place. Each quad pair carries with it one or two hexapoles and/or steerers and position-pickup electrodes, and about two meters of vacuum chamber with its thermal insulation and bakeout heaters, so that when the quads are all in place, so also is a large part of the storage ring.

The high voltage platform to house power supplies and controls for the cooling electron beam was delivered in the fall of 1986, and has been tested to -300 kV, showing an acceptably small and steady corona current (about 1 μA) to its surrounding Faraday cage. The very precisely regulated high voltage supply, which serves as the energy reference for the facility (since the stored ion beam is locked to the electron velocity by the cooling force), is completing its acceptance testing prior to delivery, so these corona tests were carried out with a secondary power supply. Fluctuations in the corona current would contribute to electron velocity fluctuations, so the high voltage tests are a significant confirmation that our terminal design is sufficiently conservative.

The solenoids that confine the cooling electron beam against space charge blowup during its passage from gun to collector are nearing completion. We expect to be mapping the confining magnetic field in the spring.

The spliiting hardware in the cyclotron switchyard that allows the beam to be diverted to the Cooler during the brief refilling intervals was installed in the June 1986 shutdown and is proving useful for sharing beam among non-Cooler experiments too. The Cooler injection beam line is under vacuum up to the bending magnet pair close to the ring.

The construction schedule calls for injection beam line tests in the spring; ramping tests of all the lattice magnets in the second quarter as the vaccum enclosure is completed; injection, accumulation and acceleration tests with the ring in the autumn as the electron system is being tested; and stored beam cooling tests with first experiments beginning next winter. This is an ambitious schedule which we are working very hard to maintain.

The average effort devoted to the Cooler construction project by the laboratory during 1986 was 29 FTE (full-time-equivalent) persons, exactly the level projected for 1986 in the 1985 planning. The Cooler effort is drawn from a much larger pool of IUCF staff, so maintaining the desired activity level requires careful balancing of many demands on a fixed total. For the next few months of peak installation workload the rate will be more than 35 FTE, tapering off into the testing and retrofitting activities of the startup period.

The construction budget passed the "90% committed" point near the end of 1986, and the orderly transfer of personnel costs from the construction project to the operations budget, associated with the transition to full operation, is underway.

Experiments have been assigned space in the G and A straight sections for the startup period, and preparations for these are described in Section III B.

Cooler Construction - T. Sloan

Dipole Magnets

This past year saw the completion of the assembly of the 12 dipole magnets at Fermilab. After the magnets were delivered to IUCF, the coils were installed and the magnets were readied for the field mapping. This entailed the design, fabrication, and installation of water manifolds, the power connections, coil interconnections, and alignment fixtures. The magnets were installed and aligned on the mapping table. Magnet field maps were made at four fields, and numerous field vs. current measurements were made. The latter are used to generate appropriate power supply ramps for use when increasing the beam energy in the cooling ring. After field mapping, the magnets were placed on their supports and optically aligned. Power, water, and interlock connections were completed and the magnets were energized.

Quadrupole Magnets

The assembly of the 36 quadrupole magnets at Fermilab was completed. The quadrupole coils are manufactured by an outside vendor, but the current leads are not terminated. The coils are inserted into a quad half, shimmed to the proper location to insure that they are symmetrically located. The leads are then bent, cut to the correct length, and have water fittings soldered on their ends. The coil current connections are then installed. Production lines to complete all these tasks were set up. The first field maps using a rotating coil field mapper were made. A device to locate the magnetic center and provide an optical alignment target was developed and tested.

3. Vacuum System

Detail design of the vacuum pipe for the 18 quadrupole pairs was completed. These pipes contain the beam position monitor electrodes and are usually terminated with a vacuum pump. Pump locations become fixed points with bellows between them to allow for thermal expansion. The quad vacuum pipes account for apporximately one third of the ring circumference. Bake out tests were run with both quad pipes and dipole vacuum cans inserted into their respective magnets. This allowed us to determine the power required for a 300° C bakeout. We also demonstrated that the insulation thickness available is adequate to prevent heat damage to the epoxy bond in the magnets.

4. Beam line 9

This beamline connects the cyclotron beam switching network to the cooling ring. Installation of this beamline is about 90% complete. This includes magnet installation and alignment as well as the vacuum system installation. First vacuum tests were satisfactory but we still have to demonstrate that the differential pumping will allow us to connect the cyclotron beamline to the cooling ring.

The Electron Cooling System - T.J.P. Ellison, O.C. Dermois, D.L. Friesel, and G. Donica

Introduction

The overall design of the electron cooling system is presented, and the magnetic guide field, high voltage, gun, collector, vacuum, and drift and clearing electrode system designs are discussed in more detail. The report concludes with a short summary of the construction schedule.

The electron cooling system design parameters are summarized in Table I.

Table I. IUCF Electron System Design Parameters

Electron Beam Energy..................	7-275 keV
Electron Beam Current..................	0-4 Amperes
Electron Beam Diameter.................	2.54 cm
Electron Gun Perveance	0.7×10^{-6} $A/V^{3/2}$
Transverse Electron Beam Temperature ..	0.1 - 0.2 eV
Electron Gun Accelerator Column Length.	62.3 cm
Max. Column Electric Field Gradient....	11.3 kV/cm
Nominal Solenoidal Magnetic Field......	1.5 kG
$B_{\perp}/B_{\parallel}$ in the Cooling Solenoid..........	$< 0.5 \times 10^{-3}$
Effective Cooling Region Length	270 cm
Collector Efficiency	>99.9%

General Layout

The general layout of the IUCF electron beam cooling system is shown in Fig. 1. The entire system is mounted on a reinforced concrete block with a rail system facilitating the movement of the system out of the ring for field mapping, off line beam testing, modification and repair. The gun and collector solenoids are also mounted on separate rail systems providing easy access to the gun and collector systems.

The gun and collector systems are cantilevered from the toroid flux return plates and kept in compression by three Vespel rods loaded by Belleville washers.

Magnetic Guide Field System

The five major components of this system[1] are the gun, collector, and main cooling solenoids, and the two 60° toroids. All the solenoids operate in series. The solenoids are being manufactured by Sigma Phi, in

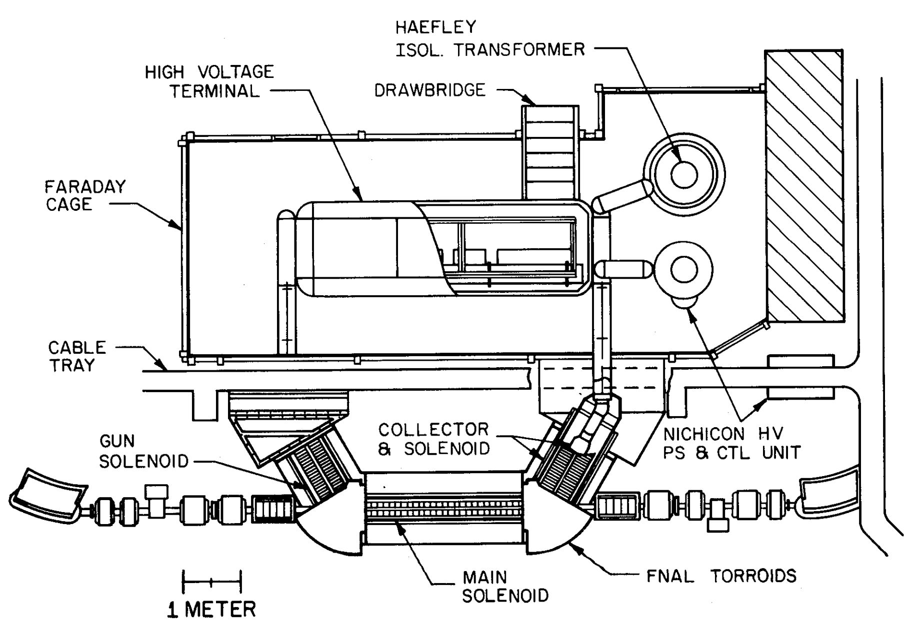

Figure 1. Layout of IUCF electron beam system.

France, and will be delivered in March 1987. Of these, the main solenoid is the most critical, since for optimal cooling, the radial field component must be less than 5×10^{-4} times the longitudinal field. The mechanical specifications for the solenoid are stringent enough to insure this level of field quality and measurements show that the solenoids are being built within these specifications. After arrival at IUCF, it will be carefully mapped with Hall probes, and possibly a pencil electron beam, to document the field quality. We are assuming the field quality will be sufficient for initial use without adding correction coils; if correction coils could significantly increase the field quality, they will be added later during a Cooler shutdown.

The toroids are from the Fermilab electron cooling system[2].

Correction and Trim Coils

There are a number of trim and correction solenoids to shape the field at the gun and collector, and correct for "missing turns" at the solenoid/toroid interfaces. All these solenoids, with the exception of the collector trim solenoids, operate in series with the main solenoid current.

The trim solenoid on the gun slides over the main gun solenoid and is used to compensate for the "open-end" effect of the solenoid and provide a uniform field at the cathode.

The two trim solenoids on the collector side are used for the opposite reason--to encourage the field fall-off in the collector region. Assuming the backscattered electrons from the collector move in an adiabatic fashion, the collection efficiency will be increased as the field at the collector is reduced, since $p_{\perp}^2/B$ is conserved.

There are also 2 coils at each interface between the solenoids and the toroids (8 coils total) to compensate for the missing turns at these locations.

Steering Dipoles

There are horizontal and vertical steering dipoles for the electron beam in the gun, cooling solenoid, and collector solenoids. The dipoles in the cooling region are used to adjust the relative angle of the electron and ion beams. The beams must be aligned to within a few hundred micro radians. These dipoles can also be used to create a large artifical electron beam effective temperature. The effective temperature of the electron beam can be estimated by measuring the minimum change in angle which produces a change in the cooling rates or equilibrium emittances. The dipoles in the gun region are used to change the relative position of the electron and ion beams in the cooling section, and can be used in conjuction with the resonant longitudinal Schottky pick-ups to explore the electron beam space charge depression[3].

Toroid Dipoles

There will be aditional dipoles in the 60° toroids. Initially, we thought that the electron beam would move adiabatically through the toroids and the function of these dipoles was merely to steer the electron beam compensating for the electron drift due to the field gradient and field line curvature in this region. However, the work done in Uppsala[4] has shown that the at relatively high electron beam energies (a few hundred keV) these dipoles must be designed so that the transverse field precisely matches the field lines radius of curvature at all points in order to keep the effective electron beam transverse temperature to a few tenths of an eV. Thus these dipoles will be designed after careful magnetic field measurements of the fields at the toroid/solenoid interfaces. Resonant focusing, as used at Fermilab or in the ICE electron cooling system gun, cannot help in damping the oscillations resulting from nonadiabatic passage through the toroids: the resonant fucusing systems cause a perturabation in the electron beam which is a function of distance from the axis of the electron beam, whereas the perturbations at the solenoid/toroid interfaces effect the beam almost uniformly. However, resonant focusing of a different sort can be used here: the electron beam can be made to adiabatically pass through the toroid providing the the beam makes an integral number of gyro-oscillations, as shown by computer simulations done in Uppsala[5]. The toroids operate on a power supply separate from the solenoid systems, so this condintion can be met in our system.

Closed Orbit Correction Dipoles

A pair of vertical and horizontal steerers are located in the ring at the entrance and exit of the electron system to compensate for the net dipole field in the toroids along the ion beam closed orbit. This four-dipole correction system enables the electron cooling system magnetic field to operate almost independently of the ring fields. The appertures and strengths of these dipoles and the voltage capability of the surplus power supply used for the electron beam guide system limit the guide field to 1.5 kG, though the guide system was designed to operate with fields in excess of 2 kG.

High Voltage System

The floor plan for the high voltage system is also shown in Fig. 1. The 300 kV high voltage terminal, housing the power supply, control, and water systems for the electron gun and collector, is constructed from 304 stainless steel and is surrounded by a galvanized steel and aluminum Faraday cage. There is a minimum spacing of 0.9 m between the terminal and Faraday cage walls. The terminal was tested at -300 kVDC and the total corona current was measured and found to be about 1 μA, which is low enough not to effect the regulation of the precision high voltage supply.

The current flowing through the gun and collector gradient resistor chains, the floating conductor covering the inside of the gun and collector solenoid mandrils, the various high voltage dividers and supplies, and the Faraday cage itself will all be returned to a copper sheet insulated from ground through separate 100 Ohm metering resisters with isolation amplifiers connected across them.

Recent tests with the Haefely 100:1 a.c, 300 kVDC voltage divider have shown that we can measure ripple voltage amplitudes as low as 0.1 V in the frequency band from 0.03 to 100 kHz.

A representatives from IUCF visited the Nichicon Capacitor Ltd. factory in Kusatsu, Japan to discuss the rigorous specifications and testing procedures for the main 300 kV, 15 mA power supply. Nichicon has agreed to a voltage ripple specification of $\Delta V_{pp}/V = 2.5\times10^{-5}$ at 300 kV with a 7.5 mA load current, and will work to achieve better than 1×10^{-5} when the supply is installed at IUCF. Preliminary test data indicate that the power supply has a short term (few hour) stability of $< \pm 5$ ppm, which is an upper limit based upon the stability specifications of the Haefely ± 5 ppm/°C dc divider. The peak to peak ripple voltage is less than 10 ppm at 300 kV, 7.5 mA, and the supply has excellent transient response characteristics. The supply will be installed by Nichicon engineers and tested at IUCF in about June 1987. A more detailed description of the high voltage system design was previously reported.[6]

Electron Gun System

The design of the electron gun and acceleration system is similar to the high perveance 750 keV system developed at Fermilab[7]. A flat, 2.54 cm diameter dispenser-type cathode is mounted in a cylindrically symmetric Pierce geometry on the axis of the gun solenoid with an anode and two guard electrodes, as shown in Figure 2.

Computer modeling studies of the electron gun, using the SLAC electron gun design code EGUN[8], were previously reported in detail[9]. Edge transverse electron beam effective temperatures of less than 0.1 eV at magnetic fields greater than 1.3 kG are predicted over the desired energy range without the use of resonant focusing.

Collector System

The IUCF electron cooling system collector (see Figure 3) is modeled after the successful Fermilab design[10] which was able to collect 99.99% of the electron beam at low energies (T<50 keV) and 99.94% at higher energies (T=114 keV). The Fermilab collector geometry was scaled down by a factor of two in diameter to match the IUCF electron beam diameter of 2.54 cm. The average collector diameter and depth are 10 cm and 14 cm respectively. There are 20 square cooling channels each with a cross section of 0.1 cm^2. A high water flow rate, 4 l/s per cooling channel, is used to provide a high value for the film coeficient keeping the outer collector surface below 100°C with 50 kW of power flowing into the copper collector (10 MW/m^2).

In addition to the change in size, a number of other changes were made to improve the collection efficiencies of the IUCF collector beyond those obtained at FNAL. These are:

1. The collector anode, which acts as a suppressor for the backscattered electrons, is split into two sections, each powered by an independent voltage source.

2. A thin (<1 micron) layer of carbon will be deposited on the inner surface of the collector to suppress backscattering. In principle this will reduce the number of high energy backscattered electrons by a factor of about three,[11] and increase the collection efficiency accordingly.

3. The collector will be operated at about 10 kV positive relative to the cathode, which is much higher than used in previous electron cooling system designs. The number of high energy backscattered electrons per incident electron, and their energy distribution (dn/dk, where k is the ratio of backscattered to incident electron energies), are almost independent of the incident electron energy.[11] Therefore, the number of backscattered electrons with enough energy to escape through the collector anode is proportional to the collector anode voltage divided by the collector voltage.

4. There are two very strong trim solenoids in the collector region providing independent control of the magnetic field at the collector and collector anode. The magnetic field at the collector can be varied from near zero to 50% of the nominal magnetic field while keeping the field at the collector anode constant. The clearance of the beam through the collector anode, which is the most severe aperture restriction in the cooling system, can also be adjusted without altering the field in the collector significantly. If the backscattered electrons move in an adiabatic fashion, the collection efficiencies will improve as the ratio of the field at the collector anode to the field at the collector is increased. The collector can also be moved, by means of a bellows, with respect to the collector anode. Moving the collector back should insure the adiabitic condition for larger differences in the magnetic field strength between the collector and collector anode, and thus, we suspect, increase the collection efficiencies.

Vacuum System

The main pumps used to reach a pressure of about 10^{-9} mb are nonevaporable getter modules of the type WP 1250/ST707. Four modules are located in each toroid vacuum chamber. Four smaller modules of the same alloy are located in the gun and three in the collector. These pumps provide a pumping speed of about 1000 ℓ/s for CO and 2500 ℓ/s for H_2 in each toroid, and about half that value in the gun and collector. To get pumping speed for the noble gases, a 30 ℓ/s triode ion pump is attached to the vacuum chamber of each toroid. Hence, the system is self supporting and can be used for off line testing. Initial pumpdowns will be done

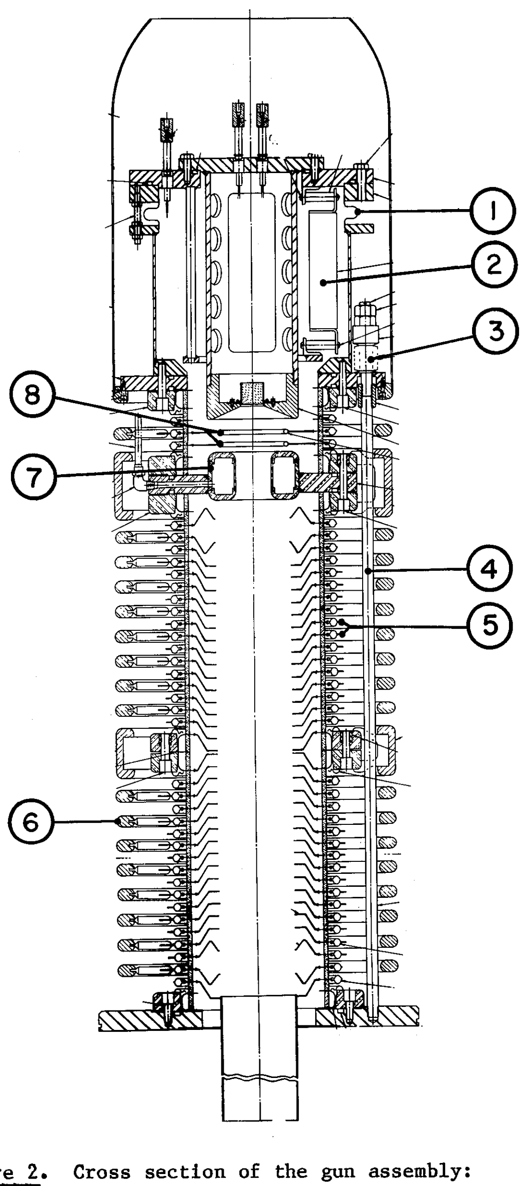

Figure 2. Cross section of the gun assembly: 1-bellows for alignment of gun; 2-one of four nonevaporable getter pumps (ST 707); 3-Belleville spring washers; 4-Vespel rods; 5-spark gaps (0.11 inch gap); 6-aluminum corona rings; 7-gun anode electrode; 8-"guard" electrodes.

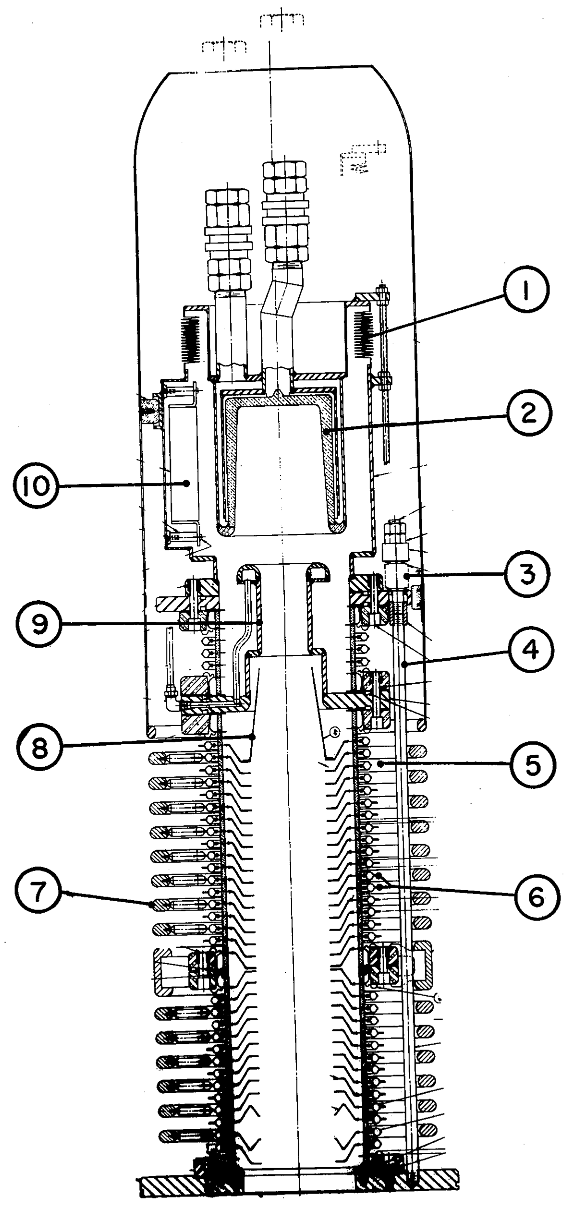

Figure 3. Cross section of the collector assembly: 1-bellows providing 6-inch movement of collector; 2-collector electrode; 3-Belleville spring washers (400 pounds force); 4-Vespel rods for compression of the cantilevered assembly; 5-area where grading resistors are mounted; 6-spark gaps (0.11 inch gap); 7-aluminum corona rings; 8-first collector anode electrode; 9-second collector anode electrode; 10-one of three nonevaporable getter moddules (ST707).

with a portable turbopump unit. The vacuum system can be baked to 300° C, with the exception of the accelerating tubes which are limited to 200° C.

Assuming an outgassing rate of 10^{-11} mb·l/(sec·cm^2) for all parts, we expect a pressure of about 10^{-9} mb in the center part of the solenoid vacuum chamber, without beam loading. The outgassing rate of many parts will be lower due to a one time pre-bake at 950° C.

Drift Electrode System

The drift electrode system is a series of 11 electrically isolated electrodes inside the electron cooling system vacuum chamber, which insure that the electron beam never sees the grounded vacuum chamber wall at any location. This system has three important functions:

1. It removes the electrons and positive ions caused by collisions between the electron beam and the residual gas atoms in the vacuum system. The electrode potentials monotonically become more negative as one moves in the direction of the collector. Thus all the ions are immediately accelerated to the collector. The electrons, however, are trapped transversely by the longitudinal magnetic field, and longitudinally by the negative potentials of the gun and collector. Split drift electrodes in the toroids are used to provide an ExB drift which is in the plane of the toroid. Depending upon the polarity of the electric field, the electrons will drift either to a resistive plate connecting the split electrodes, or to a beam stop which can be used to measure the electron current. The electrons will also drift normal to the plane of the toroid because of the gradient and curvature of the solenoidal field (centripital drift).

2. Two drift electrodes at the beginning and end of the main cooling solenoid also function as the position electrodes. The gun anode power supply has a few volts of ripple at harmonics of 30 kHz, providing hundreds of micro amperes of modulated beam current during operation. This is more than adequate for good position measurements using electronics recently developed to make position measurements of beams in excess of about 10 enA.[12] However, the ripple voltage on the power supplies which provide DC bias for these electrodes will be many orders of magnitude larger than the mV level signals induced by the electron beam. For this reason, the oscillator in the PWM circuit in the gun anode power supply will be tuned away from the frequencies of all the other switching power supplies.

3. The drift electrode inside the cooling solenoid will be powered by a 1000 V bipolar op-amp power supply with kHz frequency response. This is sufficient voltage to move any ion beam across the momentum aperture of the storage ring. This supply will be used for putting ramps on the electron beam energy and to perform experiments, such as measuring the longitudinal drag force of the electron beam. In addition, an isolation amplifier with 100 kHz frequency response will float at the potential of the 1000 V supply and directly power the electrode. This fast amplifier will be used to apply the cathode ripple voltage to the drift electrode.

Construction Schedule

The solenoids are due to be delivered in March 1987. After delivery, they will be assembled and mapped. The vacuum, gun, and collector systems will be fabricated and tested in parallel with the magnetic guide field. We expect to have completed final assembly and begin commissioning the system at low energies in the fall of 1987.

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3) This report, p. 111.

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5) Miro Sedlacek, private communication (8/86).

6) T. Bertuccio, B. Brown, G. Donica, T. Ellison, D. Friesel, J. Hicks, and R.E. Pollock, IEEE Trans. Nucl. Sci. NS-30, No. 5 (1985) 3128.

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12) This report, pg. 147 (Cyclotron Diagnostic Systems report.

Cooler RF Development - R. Poirier

Early in 1986 one of the dual gap, ferrite tuned RF cavity resonators, originally constructed for the Princeton-Pennsylvania Accelerator, was obtained for the Indiana University Cooler. Initial tests using relatively low level RF and a stand-by 2000 Amp. D.C. power supply, showed that the PPA cavity and a 4500 Amp. ferrite bias supply would be necessary to operate from about 6-20 MHz. A push-pull RF power amplifier was designed to use 4CW2000A Eimac power tubes and a Driver Amplifier module was ordered from ENI.

In July of 1986 the driver and final amplifier subassemblies were completed and the Driver was bench tested. Most of the components for the low level electronics and the frequency source were prototyped and bench tested.

By September, the amplifiers and power supplies were assembled as a test station and connected to the PPA cavity. Initial tests revealed Final Amp. plate chokes, and the input band pass filter were unsatisfactory and replaced. The earlier, low-level tests indicated that the 4CW2000A Amplifier would be optimally matched at about 7 MHz in the 6-20 Mhz hi band, so a circuit modification to improve the matching at high end, hi band was developed, using the SPICE computer program, tested and implemented. Also, one of the two PPA Cavity sections was disconnected from the load to verify that doubling the Driver and Final Amplifier RF Power would increase the output voltage approximately 1.4 times. The 6-20 MHz hi band accomdates harmonic numbers >4. A method for capacitively bandswitching the PPA cavity for a ferrite tuned 1.7-5 MHz lo band was tested and designed, to accomodate harmonic numbers <4.

Next, interconnecting and testing the Frequency Synthesizer components as NIM modules was begun, and some tests to evaluate a rectangular waveguide cavity for the UHF buncher were completed with the result that a Cavity borrowed from Fermilab for this test was too small (below cutoff) at 450 MHz. This rectangular cavity would be one wavelength long with a ceramic window at a voltage node in order to separate the tuning and high vacuum regions. Later, a half-wave coaxial resonator was designed using a cylindrical ceramic window obtained from a defective 4CW100000E power grid tube. Although the window, in this case, is located at approximately 0.6 Vmax, this design appears more efficient than the rectangular waveguide. Computer programs 'SUPERFISH' and 'URMEL' indicate that the required UHF voltage can be produced with about 1 kW of RF power. A 1 kW amplifier and a 100 watt driver were was purchased from Eimac.

By December, 1986, testing and some reconfiguring of the Frequency Source which consists of a direct digital frequency synthesizer and a tracking filter was underway. Direct digital frequency synthesizers, as we have seen, generate spurious sideband frequencies at -50 dbc levels over a frequency range which depends on the output frequency resolution. It's possible to select the resolution for sideband frequencies which are easier for the tracking filter to delete. For example, with 16 program bits, the resolution is, $F_{clock}/2^{(n+1)}$ where n=number of control bits used, typically 512 Hz, and the modulation sidebands are >65 KHz, for the least significant bit. The tracking filter is also likely to generate spurious sidebands at -35 dbc levels over a wider frequency range because they derive from harmonics of the fixed and variable high frequency components used in the tracking VCO. The sidebands generated in the VCO are not filtered.

Cooler Building Improvements - C. Nelson

A 4 1/2-ton air conditioning unit is being installed for the Cooler Computer Room. The electrical service and the major portion of the plumbing, which runs through the Swinger experimental room, are complete. We anticipate delivery of the air conditioning unit within the next six weeks and completion of this system soon thereafter.

The main air handling system in the Cooler building has been modified to improve its heating and cooling efficiency. The fan inlet ductwork was modified on exhaust fan #3, which sits outside on the west side of the building, so that this fan would no longer surge and would properly pull air across the Cooler work area. Also, return air dampers were added to the system on the mezzanine level to control the balance between return air and outside air, in order to minimize any tendency toward negative air pressure inside the building created by exhaust fan #3.

Performance tests were run by Fluid Dynamics to assess the need for further refinements to this system, and we are awaiting the results of those tests.

Cooler Controls Hardware - W. Manwaring

A 'function generator' card has been developed that drives a 16-bit DAC through 255 vectors that constitute a ramp. The ramp can be wildly non-linear. The card's memory stores eight complete ramps. The DAC is isolated. To run the ramp as a synchrotron, eighty of these cards must ramp at once.

A 'budget bakeout' system is being designed to bake out the ring to 300° C. The system will drive 140 heaters of up to 1kW. Solid state relays (10-amp) will be driven by a simple solid state 'bang-bang' controller; temperature sensing will be done with high-temperature thermistors. The 36-hour bakeout will be controlled and monitored with an IBM PC interfaced to a Keithley 200-channel ADC system.

Chassis identical to those described for the K600 Spectrograph have been built for use on the injection beamline.

A Gould 884 programmable controller will be used for beam line and ring vacuum control, although it will be controlled from a switch panel rather than from an IBM PC.

A fiber-optics link to the 300kV electron terminal is under development, using two microprocessor-driven 1553B 'smartchip' serial interface controllers. These chips drive serial (optical) lines at 1.0 Mbit/sec with Manchester encoded data. This link will allow the control computer to communicate with the DAC's, ADC's, motors, on/off controls in the terminal.

The 'big push' is now on to get all of the above completed and installed and tested in the next six to nine months.

Cooler Control System Software - J.C. Collins

All software required to drive the operator stations has been ported from DIANA to PLUTO (the cooler control system LSI-11/73), appropriately modified and debugged. The one full operator station constructed so far thus performs all the functions of the existing cyclotron operator stations. It has recently been decided that a second station must be available for cooler running. Additional parts are on order; the software was designed for multiple stations, so no major modifications are expected.

The original plan for having a separate high-speed Ethernet connection between DIANA and PLUTO has been shelved in favor of using the existing lab Ethernet system and Decnet. While the new communications method will be less responsive and may finally represent an unacceptable load on the IUCF network, both hardware and software development efforts over the last year indicate that completing the original system would be prohibitively time consuming.

Program packages have been written to allow the operator to construct pseudo-devices from linear combinations of real devices, to provide operator controlled data capture and graphic displays such as beam on target vs. time or beam vs. QUAD 2 BL3 and to perform saving and restoring of DAC values for small sets of devices, allowing good settings to be restored after an unsuccessful tuning attempt.

The core of cooler-unique software is now rapidly taking shape, at least on paper, as magnet maps are being completed and analyzed and thought is being directed to details of the commissioning phases of the cooler. The requirements for ramp generation and modification and the operator interface to the diagnostic devices are being specified.

Cooler Commissioning and Beam Diagnostic Systems
T.J.P. Ellison

Introduction

The Cooler commissioning will begin in mid 1987. A brief outline of major steps in the commissioning process and the beam diagnostic systems needed are presented along with a brief description of the status and performance specifications for the beam diagnostic systems.

Single Turn Operation

As soon as the installation of the Cooler vacuum, magnet, power supply, and control systems is completed, the ring will be surveyed with shared beam from the Cyclotrons using the newly-commissioned beam splitting system.[1] At this point there will be no injection kickers and thus the beam will be extracted after a single orbit. During this phase of commissioning, all the magnet systems will be tested, the "orbit" corrected, and the machine apperture explored. The main beam diagnostic system will be the beam position measurement (BPM) system.

Beam Position Measurement (BPM) System

There will be 37 BPM pick-up electrodes located around the ring, each providing a measurement of the beam position and intensity. The system operates with beam currents in excess of 15 nA (5 x 10^4 particles), and is capable of measuring beam position offsets from the center of the pick-up electrode with an accuracy of ± 0.1% of the pick-up diameter (about ± 0.1 mm). Thus, the accuracy of this system will be limited by the positioning accuracy of the vacuum chamber, or of the methods which we will develop to measure the position of the electrodes with respect to the quadrupoles.

Pick-up Electrodes. There are four different types of pick-up electrodes. The ceramics, electrodes, and feedthroughs have been procured and are being assembled and installed along with the other vacuum system hardware. The shunt impedance, $|Z|$, of the different electrode-amplifier systems varies from about 5 to 10 (K_h/β) Ohms, where β is v/c and K_h is a number, usually between 1 and 2, which depends upon the beam time structure. The amplifiers are connected to the electrodes with SMA connectors and 0.141" semirigid cable.

Electrode Amplifiers. Fifty electrode amplifiers[2] have now been assembled and tested, and have common mode rejection ratios varying from 40 to over 60 dB, resulting in position measurement offset errors ranging from 1% to less than 0.1% of the pick-up diameter for frequencies ranging from 2 to 20 MHz; an on-line calibration system which will be operated from the Cooler control room, however, can measure this offset error with a precision of better than ± 0.1%.

The input voltage, V, to the electrode amplifiers is given by:

$$V = I\ |Z|$$

where I is the dc beam current, and $|Z|$ is the electrode shunt impedance, defined above. The amplifier 1 dB compression point allows for operation with beam currents up to about 30 mA. However, if the beam has a "delta fuction" time structure, as will occur when the beam is electron-cooled with the rf system on, the equivalent peak input voltage is given by:

$$V = I\ |Z|/f\tau$$

where f is the fundamental beam rf frequency and τ is the amplifier high frequency cutoff time constant. Since f can be as low as 0.75 MHz in the Cooler, and τ is about 1.5 ns, the peak voltage can be almost 1,000 times higher than the amplitude of the signal voltage at a single harmonic of the revolution frequency. Thus, in certain situations, the amplifiers could saturate at currents as low as 30 μA. If it is found that the 37.5 dB gain at the electrodes is not needed to boost the beam signals above the rf interference, the amplification may be reduced to increase the system dynamic range for electron-cooled rf-bunched beams.

Multiplexing System. The rf signals from the electrodes are multiplexed to a common position detector located in the Cooler control room. The seven coaxial multiplexing stations and the control unit have been built and tested. The phase-matched Heliax cables will be installed along with the electrodes.

Low Bandwidth Position Detector. The position detector[2] has been laid out on a printed circuit card and an automatic bandwidth control has been incorporated into the ciruit. The detector has a 60 dB dynamic range for a ± 0.1% position offset error. This detector, along with the high bandwidth position detector described below, will also be used in the CELSIUS ring in Uppsala. The detector has a 100 Hz intermediate frequency bandwidth, and thus the cyclotron beam will have to be split at frequencies higher than 100 Hz to avoid a loss in sensitivity.

Stored Beam Operation

The Cooler will initially begin operation using charge-exchange, or stripping injection with 89 MeV H_2^+. In this phase of commissioning the Cooler will be the sole user of the Cyclotron beam and the goals will be to achieve and correct the closed orbit; optimize injection and accumulation; minimize the chromaticity, or optimize it to maximize the transverse and longitudinal acceptances; explore the betatron tune space around the working point; and to achieve long lifetimes.

The injected beam will debunch in less than 1 ms, so the cooler rf system will be needed at this time to preserve the coherent time structure required by many of the diagnostic systems, and to change the beam energy during measurements of the ring chromaticity and longitudinal acceptance. In addition, the control system will need application programs to correct the closed orbit, and alter the betatron tunes and the machine chromaticity.

Intensity Measurement

The most sensitive intensity monitor will be the low bandwidth wall gap monitor with an impedance equivalent to a parallel RLC circuit with R = 50 Ω, C ≈ 12 pF, and L ≈ 0.5 μH. With this monitor beams of a few nA (1×10^4 particles) can be measured with a 40 dB signal to noise ratio at reasonable frequencies.

Beam Position Measurement

rf Noise. In the cyclotron beam lines it is necessary to bunch the beam at a subharmonic of the rf frequency to elliminate rf interference[2]. The amount of rf noise from the Cooler rf system is not yet know, and thus the minimum beam current needed for measurements at the rf frequency is also not known. The Cyclotrons operate on the sixth harmonic for the 89 MeV H_2^+ beam, which corrosponds to a harmonic number of 27 in the Cooler. The injected current is maximized by pulse selecting the beam 1 in 2 using the f/2 buncher, though this prevents transferring the beam from bucket to bucket. The injected current will be lower if the beam is pulse seclected 1 in 3 using the chopper, though in this situation the beam can be transferred from bucket to bucket by operating the Cooler rf system at harmonic number 9, which is within rf system operating range for CW operation. If rf noise is found to be a problem, the cyclotron beam can be pulse selected 1 in 9 using the chopper and injected into every third of the nine Cooler rf buckets. This will reduce the current by a factor of 3, but will enable the rf diagnostics to operate free from rf interference at harmonic number three.

Position Detectors. For beam currents less than 6 μA, the low bandwidth detector[2] will be used. Its output bandwidth automatically scales with intensity according to the following relation:

$$BW\ (Hz) \approx 10\ I\ (\mu A)$$

For beam currents in excess of 6 μA the high bandwidth detector can be used. This detector has an IF of 21.4 MHz and an IF bandwidth of 600 kHz. This detector has a selectable ouput bandwidth (BW) ranging from 0.1 to 250 kHz and the noise to full scale signal ratio (N/S) scales according to the following relation:

$$N/S \approx 0.05\ \mu A/\sqrt{Hz} \cdot BW^{1/2}/I$$

This detector will be especially helpful for looking at transient closed-orbit distortions caused by mismatches in the three 1 ms fall time bumper magnets which move the beam closed orbit off the stripping foil.

Tune Measurement Systems

rf Knockout. The knockout system will be able to make tune measurements for beams with lifetimes exceeding 0.1 s and currents exceeding 10 nA.

Resonant Transverse Schottky Pick-ups. There will be both horizonatal and vertical resonant Schottky pick-ups. These pick-ups were prototyped this year in Uppsala. The pick-ups will be quarter wavelength resonators, about 1 m in length with a resonant frequency of about 60 MHz, Q of over 250, and shunt impedance of about 10 kΩ. The signal to noise with these parameters is about the same whether a transformer and low noise 50 Ω amplifier or high impedance noisier FET amplifier is used.

Since the chromaticity will be less than $\eta h/Q$, where $\eta = \gamma^{-2} - \gamma_t^{-2}$, Q is the number of betatron oscillations per turn, and h is the harmonic number at which the pick-ups operate, the signals from a coasting (i.e. nonbunched) beam will not contain useful information regarding the machine chromaticity. Since the chromaticity is also not directly observable in the transverse Schottky signals of bunched beams, the chromaticity will be measured by moving the beam within the momentum apperture using the rf system.

If the pick-up transmission lines do not extend beyond the vacuum chamber and the wave propagates along the pick-up at v = c, then the pick-up will ideally not function for beams with $\beta = v/c = 1/3$. However, by extending the transmission line outside the vacuum chamber, the resonant frequency can be shifted allowing the pick-up to work at this beam velocity. A varactor with a 5 pF tuning range will be installed at the open-circuited end of the transmission line to give the pick-ups a remote-controlled tuning range in excess of the highest revolution frequency, 2.6 MHz.

These pick-ups are also useful for measuring the beam emittance, since the signal power in the betatron sidebands is proportional to the product of the number of particles and the beam emittance.

Acceleration

The next step in the commissioning process is to accelerate the stored beam. Additional application programs will be necessary to measure and correct the closed orbit during the three second ramp, and to apply time-dependent perturbations to the betatron tunes, to the chromaticity-correcting sextupoles, and to additional magnet and rf device programs. The only additional beam diagnostic system needed at this stage is a high bandwidth position monitor located in a region of high dispersion and low beta to provide feedback for the rf system.

rf Feedback System

There are three regions in the ring ideally suited for rf feedback, with β_x on the order of 0.1 to 0.4 m, and the dispersion function (D_x) on the order of 4 m. Although these regions are reserved for experimental stations, position pick-ups are being integrated into the design of these regions. The position detector used has an accuracy of better than 0.5% of the pick-up radius (16 mm), allowing for a momentum resolution of about 0.002%, or 0.5% of the momentum apperture neglecting closed-orbit errors. If the closed orbit distortions in these regions should reach $\pm (\varepsilon_x \beta_x)^{1/2}$, where ($\varepsilon_x$) is the horizontal Cooler acceptance (25π mm-mr), a relative momentum uncertainty ($\Delta p/p$) of $\pm (\varepsilon_x \beta_x)^{1/2}/D_x$ (= ± 0.06%, or about one third of the momentum apperture) would result. However, in normal operation the closed orbit errors should be an order of magnitude smaller, and the use of multiple detectors can further reduce these uncertainties.

Electron Cooling

To assess the electron cooling system performance, it is necessary to measure the ion beam cooling rate and equilibrium emittance and momentum distribution. The cooling rate will be measured with a microchannel plate profile monitor; the equilibrium emittance with either the profile monitor or transverse Schottky pick-ups, and the equilibrium momentum distribution with the high bandwidth wall gap monitor or resonant longitudinal Schottky pick-up.

Profile Monitor

The profile monitor will use a commercial Chevron microchannel plate assembly with a 0.5 mm resolution multi-anode from Galileo Electro-Optics Corp. The electronics for this monitor have been designed by the CELSIUS group in Uppsala. This monitor will give count rates on the order of 100 Hz with a beam of a few μA and residual ring pressure of 1×10^{-9} Torr. The monitor will measure only the beam vertical profile. The electron cooling system solenoids couple the vertical and horizontal motions of the beam and will equalize the emittances in a time short compared to the cooling time. The vertical beta function at this location is about 60 m and the monitor has a resolution of 0.5 mm, or of less than 0.01π mm-mr. The monitor active area is 50 mm, which corrosponds well with the design Cooler acceptance of 25π mm-mr.

Longitudinal Pick-ups

Longitudinal Schottky Pick-ups. The rf properties for these devices will be similar to those of the transverse pick-ups. This will enable a 20 dB signal to noise measurement of the beam momentum distribution providing the beam current and energy spread fullfill the following constraint:

$$I > 100 \text{ mA } (\Delta E/E)$$

where $E = \gamma Mc^2$.

This pick-up can also be used to measure changes in the electron beam energy with a precision of 0.1 to 1 ppm. Since the ion beam γ (E/mc^2) is always much less than γ_t ($\gamma_t \approx 5$), the beam revolution frequency is about 25 times more sensitive to a relative momentum change than to a relative change in the magnetic field, which will be regulated to about 5 ppm.

This monitor can also be used to measure the electron beam space charge depression. Steering dipoles in the gun region of the electron cooling system can change position of the electron beam in the cooling region relative to the ion beam. If the electron beam is not space-charge neutralized, this will change the ion beam energy and revolution frequency. A study of the revolution frequency versus electron beam position will yield a measurement of the degree of neutralization.

Wideband Wall Gap Monitor. This monitor can also be used for mesuring Schottky signals, although the beam intensity must be more than 2 orders of magnitude greater than is needed for the resonant pick-up for similar signal to noise ratios. However, since this monitor is wideband, indirect measurements of the ion beam energy spread can be made by measuring the time spread of an rf-bunched beam, providing the beam current exceeds about 100 nA (5×10^5 particles). Although the high bandwidth wall gap monitor bandwidth exceeds 1200 MHz, the fastest oscilloscope in the laboratory is limited to 350 MHz, sufficient for measuring FWHM time spreads of about 0.5 ns.

Cooling and Heating

The same diagnostic systems used to evaluated the cooling process can also be used to measure the properties of a beam in equilibrium with the cooling by electrons and the heating by the internal target.

Conclusion

The beam diagnostic systems pressented here are a minimal set needed for commissioning the Cooler. In the future, additional systems such as a damper, a beam transfer function measurement system, and a system to nondestructively measure the tune during ramping could be developed. Future developments will depend heavily on our operational experience.

1) This report, p. 14.

2) See this report, p. 147, for more information and references concerning the BPM amplifiers and low bandwidth position detector.