THE IUCF COOLER-A STORAGE RING WITH ELECTRON COOLING FOR INTERNAL TARGET EXPERIMENTS.*

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Abstract

A project to construct a ring to store beams of light ions with magnetic rigidities up to 3.6 T-m is underway at the Indiana University Cyclotron Facility. Beams from the cyclotron will fill the ring, be adjusted in energy, then cooled by electron immersion while impinging on thin targets within the ring for nuclear interaction experiments. The motivation is to explore the potential for improved resolution and reduced background of the cold storage technique. The status of the project and of selected subsystem designs will be presented.

Introduction

Techniques for electron cooling¹ of stored particle beams, developed initially for antiproton accumulation, can be adapted to give an alternative method for nuclear scattering and reaction experiments. An ultrathin target in the stored beam path increases the beam incoherent velocity spread with each traversal. Under suitable conditions, this "heating" rate can be balanced by the cooling mechanism to attain a thermal equilibrium with useful beam quality and reaction rate (luminosity) for conducting nuclear interaction experiments. Conditions appear most favorable with electron cooling of light ion beams with $0.3 < v/c < 0.6$, which is roughly the energy range of the experimental program at the Indiana University Cyclotron Facility.

The IUCF Cooler will be a six-sided storage ring of 82 meter circumference, which will use the existing isochronous cyclotron as injector. The rigidity limit for the stored beams is 3.6 Tesla-meters. The lattice design gives considerable access for internal target experiments. Three target straight sections are incorporated in the design. Two have moderate (4m) dispersion, while one is dispersion-free for maximum luminosity in tagged secondary production. The other three long straights are used for injection, for cooling, and for miscellaneous machine functions such as acceleration, diagnostics, and so forth. Some representative ring parameters are given in Table 1.

Two injection modes are provided. A moderate circulating current of a few milliamperes will be obtained by transverse and longitudinal stacking, while charge-changing injection is to be used to obtain larger circulating currents. Provision is made for an rf cavity to permit manipulations of the longitudinal phase space after injection, such as debunching to reduce the energy spread and increase the microscopic duty factor, or energy adjustment so that the ring experiment is independent in energy choice of other users sharing the cyclotron beam. The electron region is to provide cooling of ions in the velocity range $0.20 < v/c < 0.75$. The electron source will be designed to reach 275 keV at 1 to 4 Amp., with a transverse electron temperature of 0.5 eV.

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An experimental program which exploits the potential for reduced emittance and energy spread of the cooled beams is envisioned. Experience with the cyclotron beams at IUCF has shown both the great richness of nuclear phenomena accessible with intermediate energy light ion beams and the crucial role played by beam quality in extending the precision of measurements. The ring is being designed to accommodate a pair of magnetic spectrometers at one of the internal target locations for use in both high resolution ($p/\Delta p > 20,000$) and particle coincidence experiments. The latter benefit from the 100% microscopic duty factor which is made possible in the storage mode.

An analysis of experiments proposed for the present external uncooled beams at IUCF shows that about one-third of these are planned for luminosities of about $10^{30}/\text{cm}^2\text{s}$. These include much of the He and Li beam use and some of the polarized and unpolarized H ion experiments. About two-thirds of the beam requests are for luminosities of about $10^{32}/\text{cm}^2\text{s}$. Only a few experiments making neutron secondary beams with thick targets require $10^{34}-10^{35}/\text{cm}^2\text{s}$ which is beyond the thermal runaway limit of the cooling process. The Cooler will give superior resolution and time-shared use in the 10^{30} range, while the 10^{32} range will be covered in the stripping injection mode, with beam quality better than that of the cyclotron.

Lattice Design

The ring is an irregular hexagon with alternating zero and high dispersion straight sections. Each of the six straight sections has reflection symmetry about the center and, except for the cooling straight, each has a fairly tight waist, with a long drift space for experiment access. The injection "straight" has a 60° bend in the center associated with charge-changing injection. The adjacent corner dipoles are a pair of 28.5° uniform field $\rho=2.25\text{m}$ bends, while other corners have a pair of 30° bends. For maximum flexibility there is only one superperiod.

The separated function focussing is provided by 36 quadrupole singlets. The two quads on either end of a dispersed straight give a fixed value for β and dispersion, whereas the four quads bracketing each non-dispersed straight give flexibility of adjustment of ring tune or of waist size. The aperture function in the horizontal plane β_x varies from a maximum of about 150m in the bends to a minimum of about 0.1m at the target waists. The range of β_y is similar. The acceptance in both planes is $12\pi \text{ mm-mrad}$. The aperture limit to momentum acceptance is $\pm 0.2\%$. Chromaticity correction is required as discussed below.

The large product of β function with lens strength combined with the low symmetry of the lattice leads to stringent requirements on the quadrupole magnet field quality, typically at the level of 10^{-3} in the gradient. The quadrupole magnets have 10 cm diameter with 8 cm available for beam after allowance for baking thermal insulation and vacuum wall. The field quality requirement and the small acceptance for this field volume are both part of the price paid for the unconventional lattice which makes possible dispersion-matched scattering experiments and large resolving power in the stored beams.

Chromaticity Correction

The Cooler lattice is designed to have a large resolving power by making the beam wide in the dipoles. At the target waists, the requirement of high luminosity leads to small beam size. The horizontal aperture function β_x is about 150m in the dipoles and 0.1m at the spectrograph target. The target straight sections have a length of about 6m to give experimental access. This configuration leads to an unusually large chromaticity ξ (rate of change of tune with momentum).

The chromaticity can be shown² to be :

$$-4\pi\xi_x = \sum (\beta_x \cdot LB' / (B\rho))$$

summed over all ring elements. The length-gradient product of a focussing element divided by the beam rigidity is the strength of the element (inverse of the focal length for a thin lens), and is counted as positive if focussing and negative if defocussing. Strong lenses at the ends of a long straight section containing a small beta waist contribute especially to this sum. Because of the large β_x in the corner dipoles, the chromaticity sum must take account of the change with momentum of the dipole bend radius, the change in path length in the dipole and the changes in angle of crossing the field boundaries. The dipoles account for about 2/3 of ξ_x , while the quadrupoles are responsible for almost all of the vertical chromaticity ξ_y .

The physical apertures of the lattice magnets, in combination with the dispersion function, set a limit to the momentum acceptance of the ring. A large

Figure 1. Floor Plan of IUCF Cooler. The beam from the cyclotron (not shown) enters from the lower left where it is diverted upward into the Cooler building in addition. The space to the upper left is reserved for a future "Tripler" (booster cyclotron) shown in outline. The shielded stairs lead up to a power supply/controls/data area. The electron cooling straight is the one upstream of injection.

chromaticity may give a more restrictive limit by shifting parts of the beam momentum distribution into a region of the tune diagram containing resonances. Chromaticity correction is added to the lattice to retain the full momentum acceptance.

The traditional method of correcting the chromaticity is to install hexapole elements in regions with non-zero dispersion. Off-momentum particles then encounter additional focussing strength from the position-dependent gradient in the hexapoles. The hexapole strength may be adjusted to cancel the natural chromaticity.

The change in focussing element strength with momentum has a second important consequence. The off-momentum particles see a mismatched lattice with the result that the beta functions develop modulations leading to a reduction in the transverse acceptances. The effect is the same as the development of a momentum-dependent width to the half-integer stopbands. The distribution of hexapole strength must take account of the stopband driving by cancelling the appropriate Fourier coefficient.

The hexapoles may also drive the third-integer stopband for all momenta. Cancellation in general will require additional hexapoles, which can be located in non-dispersed regions where they have no effect on chromaticity or the off-momentum half-integer stopbands. For each of the two transverse dimensions there is thus a chromaticity and two complex amplitudes to be controlled for a total of ten independent conditions or a minimum of ten hexapole adjustments³.

In large machines it may be possible to exploit the symmetry to place hexapoles in families which independently control these ten variables. The IUCF Cooler lattice has superperiodicity of one and it is by no means obvious that it is possible to find hexapole locations suitably spaced in betatron phase to permit the necessary cancellations, much less to obtain independent control. We have found however that there is a satisfactory scheme for hexapole placement in the Cooler which is briefly described below.

The cooler lattice has essentially identical lattice functions in each of the six corners with reflection symmetry about the waist in each long straight. The small beta waist in each dispersed straight section gives nearly a 180° phase shift between the ends of the straight. Hexapoles at each end act constructively in cancelling both the chromaticity and the driving of the half-integer stopband, while they are nearly out of phase in driving the third-integer stopband. Furthermore there is only a small phase advance in the horizontal plane in passing the corner dipoles. The vertical motion goes through a tight waist in the corner so that there is a nearly 180° advance in this plane. As a fortunate consequence, the hexapoles placed symmetrically near the ends of the long dispersed straights turn out to effect most of the required dispersion cancellation and stopband control despite the variations in the lattice functions among the different non-dispersed straights.

Because the chromaticity is fairly large, the hexapole strengths are appreciable. It appears to be necessary to incorporate some hexapole strength within each of the twelve quadrupole elements in the dispersed straights. By including in the lamination stack a variable fraction of laminations which contain a deliberate departure from four-fold symmetry, the hexapole fraction can be chosen at will. These fixed corrections will be supplemented with discrete hexapole elements to obtain the exact ten parameter adjustment. Calculations show that cancellations at the level of a few percent or better are possible with the fixed corrections alone for a given lattice configuration. The role of the variable hexapoles is to permit some tune variation, such as a variable β in the cooling straight.

Hexapole pairs in quadrupole doublets at locations where the horizontal and vertical beta functions are maximum can be driven in linear combinations which affect the two transverse dimensions independently. The six-by-six matrix inversion is thus reduced to two three-by-three and three two-by-two which are readily accomplished. The ring is divided in three regions centered on the three dispersed waists. The hexapole strength which locally cancels the contribution from this region to the chromaticity is found also to very nearly cancel both the sine-like and cosine-like off-momentum half-integer stopband-driving terms in each transverse dimension. This is most fortunate because the relative phasing between these three regions is strongly affected by the variations in the choice of tune in the non-dispersed straights, so that more exact cancellation can be obtained only at the expense of severe restrictions on the flexibility of the lattice setup. The third-integer stopband driving

terms are minimized by slight imbalance between upstream and downstream hex doublets, and if necessary by additional discrete elements in the non-dispersed straights.

A complication in the hexapole placement arises from the desire to use the third of the ring upstream of the spectrograph pair as a high resolution analysis system for non-recirculated beams. RAYTRACE calculations show that the hexapole strengths appropriate to chromaticity cancellation for the circulating beams are about four times too strong for optimum resolving power in use as a momentum analyzer. The present plan is to distribute the hexapole strength between a 60% component built into the quadrupoles and a 40% (reversible) discrete component so the strengths add for the storage mode and largely cancel for the one-pass mode. It is not possible to make all the hexapole strength by discrete elements because of space restrictions.

The perturbation analysis of the lattice focussing strength distribution, which gives the hexapole placement and strengths, also is informative in establishing criteria for the stability and uniformity of quadrupole fields. A change in an individual quad strength shifts the tune and creates a half-integer stopband which reduces the transverse acceptance. The sensitivity in the horizontal plane to power supply ripple is greatly reduced by operating the quadrupoles in series-connected doublets and adjusting the length of the lamination stack to obtain the required strength ratio. A small trim coil in figure-8 connection gives a fine control of the strength ratio. Unfortunately the same degree of sensitivity cancellation is not obtained in the vertical plane and leads to the accuracy requirement of order 10^{-3} . There are examples in the literature⁴ of quads with more stringent field purity specification but this is clearly a severe consequence of our design. The usual method of exploiting a superperiodicity of two, and of connecting quads on opposite sides of the ring in series, is not useful for the Cooler so the power supply ripple, stability and absolute accuracy specification is not much relaxed by series connection schemes so the choices can be made on purely impedance-matching and economic grounds.

The questions regarding higher order ring correction are still under study. The hexapole scheme which zeroes the appropriate Fourier integrals (J_0 and J_{11} in the notation of ref. 2) does not completely remove the beta function modulation for off-momenta beams in our SYNCH studies, for reasons not yet fully understood. The calculated chromaticities do become small. For third and higher order corrections it is clear that the section used for one-pass momentum analysis will need two octupole elements to cancel the (x, θ^3) and $(x, \theta\phi^2)$ aberrations at the target. For the circulating beams it is necessary to consider both the natural components and the higher order effects of the strong hexapoles. The criterion for deciding whether control elements are necessary will be to determine the boundary of the stable region in a given order of perturbation and then ensure that the physical apertures set the acceptance limit in each case.

Electron Cooling Region

We plan a conservative approach based on tested performance and design experience of other groups to make a workable electron beam device. Our design work has just begun. The only new feature is the short strong reversed field solenoid beyond either end of the electron beam path which maintains the transverse polarization state of a stored beam and reduces the coupling between transverse dimensions introduced by the longitudinal confining field solenoid for the electrons.

Table 1. Some Cooler Ring Parameters

Injection

Beam properties:

Acceptance $A_x=A_y=12\pi \cdot 10^{-6}\text{m}$, $\Delta p/p=\pm 0.2\%$	
Rigidity range	$0.65 < B\rho < 3.6 \text{ T}\cdot\text{m}$
Velocity range	$0.2 < v/c < 0.75$

Ring dimensions:

Ring circumference	82.12 m
Betatron frequencies Q_x, Q_y	5.43, 5.42
Electron cooling straight ($\beta_x=\beta_y=6.5\text{m}$, $p\partial x/\partial p=0.0\text{m}$)	6.60 m
Two dispersed target straights, each ($\beta_x=0.11\text{m}$, $\beta_y=0.5\text{m}$, $p\partial x/\partial p=4.05\text{m}$)	5.99 m
Two non-dispersed target straights, each ($\beta_x=\beta_y=0.32\text{m}$, $p\partial x/\partial p=0.0\text{m}$)	3.96 m
Injection "straight" (6° bend) ($\beta_x=0.12\text{m}$, $\beta_y=0.34\text{m}$, $p\partial x/\partial p=4.12\text{m}$)	5.58 m

Dipole magnets:

Number (4 @ 28.5° , 8 @ 30° , 1 @ 6°)	12	
Radius	2.25 m	
Maximum field strength	1.6 T	
Total gap	5.2 cm	
Beam aperture (full height)	3.7 cm	
(full width)	8.6 cm	
Total power dissipation (1630 A, 130 V)	210 kW	
Stored energy	230 kJ	

Quadrupole magnets:

Number (10 @ 52 cm, 18 @ 32 cm, 8 @ 18 cm)	36	
Pole tip aperture radius	5.0 cm	
Beam aperture radius	4.3 cm	
Maximum tip field	0.7 T	
Total power dissipation	200 kW	
Stored energy	30 kJ	

Electron beam:

Maximum energy	275 keV	
Beam radius	10 mm	
Maximum current density	1.2 A/cm ²	
Maximum beam power	1 MW	
Electron temperature (rms)	< 0.5 eV	
Confining field	0.15 T	

The ring transverse acceptance exceeds the cyclotron emittance by about one order of magnitude in each dimension. In the longitudinal space, the ring momentum acceptance exceeds that of the cyclotron beam by a factor of ten while the ring circumference is larger than the cyclotron beam bunch length by a factor of 10^3 . The cyclotron beam bursts are exceptionally narrow in time not only because of the rapid, isochronous acceleration but also because the rf voltage increases during acceleration (varies with radius) so that there is a phase width compression⁵ by a factor of more than three.

An individual beam burst from the cyclotron now contains on the order of 10^6 particles. The ring confinement limit lies in the range 10^9 to 10^{11} particles depending on energy and the degree of cooling. By modifications to the cyclotron it will be possible to raise the pulse intensity to about 10^7 ppp. at reduced repetition rate. Longitudinal space charge effects begin to reduce extraction efficiency⁶ unless the pulse spacing is increased. The task of the injection system is to use the available phase space volume ratio of about 10^6 to obtain stacking factors in the range 10^2 to 10^4 .

We are planning two injection modes. For high resolution experiments, in which the beam is cooled to a phase space volume very small in comparison to the ring acceptance, and the space charge tune shift limit to stored particle number is of order 10^9 , we plan to use a combination of transverse and longitudinal stacking schemes to stack about 10^2 turns. In this mode the cyclotron operation is time-shared between intermittent ring filling and experimental use between fillings. The emittance and momentum spread of the stored beam are degraded by the end of the fill cycle relative to the cyclotron beam in this mode, but the cooling process restores and improves the beam quality so the ring experiment is carried out with a beam quality determined solely by the thermal equilibrium between target heating and beam cooling.

For the higher luminosity experiments the target thickness is increased so the thermal equilibrium beam volume in the transverse phase space is comparable to that of the raw cyclotron beam. The space charge limit on stored beam intensity is higher than the limit to stacking by practical methods within the acceptance restrictions. We therefore plan a second injection mode which makes use of the availability of non-fully-stripped ions such as H_2^+ , He^+ , and Li^{++} from the IUCF cyclotron. The beam is stripped onto the ring equilibrium orbit in a manner which exploits the low particle density relative to the quantum limit and permits the apparent violation of the Liouville theorem to achieve large stacking density with limited emittance growth⁷. Even after allowing for the growth in longitudinal phase space dimension, the desired equivalent stacking factor of 10^4 should be achievable.

The cyclotron rigidity limit of 2.2 T·m gives rather lower energies of the stripped beams relative both to the rigidity limit of the Cooler ring and to the needs of the experimenter. The ring design therefore allows for the acceleration of the beam after filling and prior to cooling and the carrying out of the experiment. Time-shared use of the beam available between fillings to non-ring users will not normally be attractive in the stripping injection mode in view of the energy restriction set by the cyclotron. The typical ring cycle in this mode will include a 2 second magnet ramp during acceleration, about 1 second of precooling before data-taking commences and after 2 to 20 seconds of experiment, about 1.5 s to ramp down and

a fraction of a second to refill. The macroscopic duty factor in this mode of 35% to 80% is thought to be generally acceptable. For no energy change, the 3.5 s for magnet ramping is deleted from the fill cycle.

The injection straight section contains a set of Lambertson style septum magnets which allow the choice of stripping or of non-stripping injection without breaking vacuum. The 6° magnet at the center of the straight section gives a path separation so the incoming beam, which has different rigidity prior to stripping, can clear the ring quadrupoles magnets. The incident trajectory in the non-stripping mode passes through a field-free aperture above the ring midplane in the 6° dipole and is bent into the midplane in the final small septum magnet.

Target Considerations

The rate of electron cooling sets an upper limit to the usable target thickness for a given energy resolution which is in the neighborhood of 10 to 100 nanograms/cm², averaged over a cooling time constant. A spatially localized target which intercepts a small fraction of the beam area can be thicker. Quartz fibers of about 1 μ m diameter (200 μ g/cm²) have been used as internal targets⁸ and will be employed in initial ring performance tests. Such a fiber will intercept about 0.1% of a 1 mm beam spot and will act as equivalent in beam heating or luminosity to a full width target of 200 ng/cm². Carbon fibers, single crystal whiskers, and fibers with evaporated coatings of separated isotopes will extend the fiber target technique to a reasonable portion of the nuclear species of interest to users.

A spatially-localized target at a momentum-dispersed waist gives most of the improvement in resolution possible with dispersion-matching for spectrograph scattering experiments without an exact matching condition. The lattice design is simplified by not requiring the dispersion to be adjusted for differing reactions and scattering angles.

The experiment luminosity will be continuously measured by four small angle elastic scattering monitors at the entrance of the first quadrupole magnet downstream of the target. These also provide beam angle information. Circulating current is to be measured independently by a second-harmonic DC transformer so the average target thickness may be calculated. Note that if the beam spot is stepped across a fiber target, the event rate directly measures the spot profile and hence the emittance, provided the sweeping rate is fast compared to the cooling rate. A slow sweep allows the beam emittance to change in response to the varying fraction of the beam passing through the target and gives additional information about the cooling rate. We expect that many of the ring diagnostic measurements will develop from interactions between ring performance and experimental data, of which this is one example.

For the thinnest targets, at least one target straight section will be equipped with the additional differential pumping to permit the use of a vapor jet or cluster jet target. Apart from the obvious vacuum system complications, such targets are known to drive the "throbbing mode" and related transverse instabilities⁹ which will reduce the luminosity with gas targets relative to solid targets. A preliminary estimate places this limit in the vicinity of 10^{32} /cm²s with no active damping. The driving force comes from a time lag in the decay of an ion cloud left behind by a moving beam and is worst at low energy, high gas pressure, small beam spot size and large circulating current; all of which are present for a high luminosity jet target experiment in our ring.

Space precludes an extensive discussion of thin polarized target plans. This is a rapidly developing technology¹⁰ and will be used in the IUCF Cooler in conjunction with stored polarized ¹H & ²H beams.

Project Status

The Cooler design began in 1979. The project was formally proposed to the National Science Foundation as a facility upgrade to IUCF¹¹ at the beginning of 1981. A favorable recommendation by the Nuclear Science Advisory Committee led to the appearance of the Cooler project in the FY1983 federal budget. The project has been receiving preliminary R&D funding since the beginning of 1982 and construction funding may begin in 1983. A building addition to house the ring and its experiments is to be provided by Indiana University.

The projected cost for the Cooler ring is approximately \$6.5M (1983\$) with an additional \$1.4M for the spectrometer pair under separate equipment grants to Indiana and Maryland user groups. The building addition will require an additional \$2.7M.

A variety of lattice designs have been evaluated in the process of arriving at the choice described above. The programs TRANSPORT and SYNCH have been employed in the design phase. The program RAYTRACE has been used to examine higher order effects in passing the beam to the spectrograph target.

Studies of vacuum construction technique and of bakeout procedure have been carried out on a 10^{-9} Torr test stand which has been in operation since October 1982. We have used a laminated dipole on loan from FNAL to begin development of magnet ramping and field measuring procedures at the level commensurate with the stringent requirements of this lattice.

Given construction startup in 1983 and a schedule of funding spread over the calendar years 1983-85, we are proceeding on a schedule which will allow installation within the new building to begin in 1985 with the first beam tests in 1986 and the first experiments in 1987.

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