THE INDIANA COOLER PROJECT - 1986 STATUS REPORT*

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Summary

The IUCF Cooler is a synchrotron-storage ring with electron cooling, which is designed to accommodate a diverse program of internal target experiments in intermediate energy nuclear science, accelerator physics, and adjunct areas. The project concept has evolved significantly over the six years since first formally proposed. The factors affecting its use as a research tool are reviewed in the light of our current understanding, with particular attention to the limiting phenomena which define the performance envelope. Construction began in 1983, installation is now underway, and first operation is expected in 1987.

Introduction

The Indiana University Cyclotron Facility (IUCF) began operation at the end of 1975.[1] It is operated as a national user facility in intermediate energy nuclear science, and has provided beams for experiments by some 350 scientists from 60 institutions in 13 countries. The 2 Tesla-meter isochronous cyclotron provides beams of atomic mass $1 \leqslant A \leqslant 7$. Proton kinetic energies from 12 to 215 MeV have been delivered to experiments. About 2/3 of the running time is devoted to polarized $^1H^+$ and $^2H^+$ ion operation.

The continued heavy demand for IUCF beams can be understood in part by the fact that the upper end of the IUCF proton energy range overlaps an energy window (roughly 150-350 MeV) in which the nucleus has maximum transparency, and in which spin effects are strong and selective, and in part by the excellent beam quality (intensity, emittance, resolution) which has permitted detailed examination of individual nuclear excitations. Progress in our understanding of the physics accessible to this energy region has been rapid over the past decade, and the contribution of the IUCF facility to this effort is a matter of some pride to the operating and research staff.

The IUCF beam quality is of particular importance in the examination of low cross section reactions where high resolution is mandated by the need to discriminate against interfering nearby excitations. The cyclotron beam is bunched to a time width of about 0.3 ns fwhm, so the coherent energy spread arising from isochronous acceleration on the peak of the 25-35 MHz rf waveform is $\leqslant 0.1\%$ of the kinetic energy. Beam transport lines are designed for dispersion-matching at selected target stations to further improve the observed resolution. A QDDM magnetic spectrometer[2], in use from 1976 to 1985, was able to reach resolutions of about 40 keV at 100 MeV and 75 keV at 180 MeV. The lab has recently begun commissioning a new 3.6 T-m higher resolution spectrograph with the design goal of 20 keV at 200 MeV. The major effort and expense being committed to the development of this new instrument underscores the continuing important role of superior resolution in the research program of the laboratory. When proper matching conditions are achieved, the resolution in an experiment is limited by the width of a monoenergetic waist near the target location. Even lower emittance than the $1\pi/\beta\gamma$ mm-mrad of the IUCF cyclotron beam would be required to further improve the resolution with a magnetic system of practical dimensions.

One of the major components of the IUCF research program has been the study of threshold pion production[3] on nuclear targets. The beam energy of the IUCF cyclotron has been too low to reach the nucleon-nucleon thresholds near 275-300 MeV, and gaps in our knowledge of this fundamental process, in conjunction with a certain theoretical intractability associated with the high momentum transfer that leads to the small cross sections, has been limiting progress in our understanding of the nuclear reaction. The desire for better nucleon-nucleon pion production data near threshold is only one example of the need for beams of IUCF quality at somewhat higher energies than the limit of the 2 T-m cyclotron.

At the end of 1980, a facility improvement program was proposed for IUCF, using the technique of electron cooling in a storage ring to obtain improved beam quality. The 3.6 T-m rigidity of the ring was selected on physics grounds to give access to proton energies up to 500 MeV, and $Q/A = 1/2$ ions to 150 MeV/amu.

By laminating the magnets of the ring, and by incorporation in the design of acceleration cavities and ramping power supplies, the ring can function as a slow-cycling synchrotron to reach the higher energies after injection by the cyclotron. The deterioration of beam quality, which accompanies multi-turn injection to build up large circulating currents, is removed by electron cooling after acceleration.

The slow cycle implies a low average beam current. The cooling takes a few seconds, so more rapid cycling would give little gain. However by operating with sufficiently thin internal targets, and cooling while the target is in the beam, a very efficient use is made of each beam particle. The predicted event rates, in experiments with internal targets and simultaneous electron cooling, are similar to those encountered in typical IUCF cyclotron experiments, while the cooled beam quality can be superior to the cyclotron beam (in emittance and energy spread) by about one order of magnitude.

The "IUCF Cooler" was recommended for construction following a review by the Nuclear Science Advisory Committee in 1981, and construction funding began in 1983. Ring components are now being installed, and we are about a year away from startup.

In the period since the proposal was written, there has been a continuing effort to understand operation in a cooled, storage mode. Conceptual planning of experiments in the Cooler has been an essential input in the evolution of the design.

In this paper we summarize our current understanding of the ring behaviour from the standpoint of the user. A recent companion paper[4] updates some of the technical features of the design.

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*Work supported by the U.S. National Science Foundation under grant NSF PHY 82-11347

Performance Envelope

Energy

Upper Bound. The cooling electron beam velocity must equal the stored ion beam velocity, so the electron kinetic energy is lower than the ion kinetic energy per atomic mass unit by the mass ratio (1,822.8). An electron kinetic energy of 272.3 keV allows cooled proton (1.0073 a.m.u.) operation at 500 MeV. This energy also establishes the upper limit to the design rigidity at 3.636 T-m.

The ring can operate as a synchrotron to permit injection at one energy with the experiment carried out at another energy. The magnets and power supplies are designed to ramp the rigidity at rates up to 1.0 T-m/sec. A slow ramp is sufficient because the ramp time need only be comparable to the total cooling time to ensure that the average current and duty factor are not greatly reduced when acceleration is employed.

The Cooler ring dipole magnet maps[5] show that the 500 MeV design goal for protons is within the operating range of these components, although the onset of saturation will make the ramping process more delicate above about 400 MeV, requiring extra development time to verify the entries in the table of slope and endpoint vectors which are used by the ramping hardware to generate the appropriate nonlinear dI/dt curve.

Lower bound. The lower bound of the operating range is chosen to permit injection by stripping of 44 MeV $^4He^+$. To cool this beam requires 6.0 keV electrons. While such low energies lie well below the range of interest to much of our research program, they will permit calibration and resolution tests, such as the lowest T=3/2 state of ^{13}N, of width $\Gamma = 1.1$ keV, which may be seen as a resonance in elastic scattering of protons by ^{12}C at 14.232 MeV while cooling with 7.75 keV electrons.

The low energy operation of the Cooler is the most demanding, both because of the more rapid loss rate by ion scattering in the residual gas, and because of the reduced electron current for cooling at lower energies due to space charge (perveance) limits in the electron gun. We have chosen to optimize the design by using a constant electron current for the 100-300 MeV/amu operating region, and to accept lower performance at energies below about 50 MeV/amu.

Emittance and Energy Resolution.

Prediction of the equilibrium phase space distribution of a stored ion beam, cooled by electron immersion and heated by an internal target, by residual gas, by intrabeam scattering, by fluctuations in lattice element and electron region power supplies, and by various coupling effects, is a matter of considerable complexity. Verification in a working ring is needed to reduce uncertainties in this exercise. A full discussion of the physics involved lies well beyond the scope of this article. We make here only qualitative statements about a few reasonably well established consequences.

Dispersion. The lattice functions such as the dispersion $\eta_x = p\cdot dx/dp$, the angular dispersion $\eta_x' = p\cdot d\theta/dp$, and the aperture function β_x which relates the monoenergetic beam size and divergence to the emittance ε_x at a waist: $\varepsilon_x = \pi\cdot x^2/\beta_x = \pi\cdot\beta_x\cdot\theta_x^2$, vary with position in the ring, and in principle may be freely chosen, within broad limits, by the ring designer. The combination $h = \eta_x^2/\beta_x + \beta_x\cdot\eta_x'^2$ is a measure of the resolving power at a waist and is particularly important to the equilibrium properties of the phase space distribution. Where h is large there is strong "synchrotron-betatron" coupling between longitudinal and transverse phase space dimensions.

This coupling can have both beneficial and detrimental effects. Dispersion-matching in a beam line is in essence the exploitation of a large h value to obtain better overall resolution in a scattering experiment than the momentum spread of the beam would otherwise allow. In a ring, the beam would pass through such a large h region many times. Weak processes that might be safely ignored in a transport line may develop cumulative consequences. For example a static spatial non-uniformity in the target density (a component in the dispersed plane of a thickness gradient across the beam spot) leads to rapid tranverse heating and equally rapid longitudinal cooling if the target is thicker on the high momentum side, or the converse if the sign of the gradient component is reversed. If the growth rate of heating by this process exceeds the electron cooling rate, the beam will be lost by thermal runaway.

Large momentum transfer collisions of ions with electrons in the target, which lead to a "δ ray" tail on the low side of the momentum distribution, can in the presence of an appreciable h value lead to the development of a tail on the transverse emittance distributions, and, for large enough h, even to an additional single scatter loss mechanism that reduces the beam lifetime. The threshold for this loss is easily estimated for non-relativistic beams where the maximum δ momentum transfer $\Delta p/p$ is twice the electron/ion mass ratio. For an acceptance of 25π mm mrad as in the IUCF Cooler, for example, the value of h should be below 30 m for proton operation, to avoid this loss mechanism.

Intrabeam Scatter. Beam particles scatter in each other's Coulomb fields. For a scattering event which takes place where h = 0, the intrabeam scattering leads to exchange of temperature among the phase space dimensions, in the direction of isotropy. But where h is large, the result of this intrabeam scatter is a self-heating of the beam in both longitudinal and transverse planes. When a two-particle scattering event converts incoherent transverse momentum into longitudinal in a region of finite h, the changed momentum moves the equilibrium orbit away from the particles' position, and thus regenerates a transverse oscillation amplitude on subsequent orbits, effectively converting some of the large coherent momentum of the beam into an incoherent thermal form. The heating rate is proportional to the beam phase space density and to a suitable average of h over the ring circumference. The average can be dominated by the presence of highly resolved waists.

An attempt to improve resolution in a stored beam experiment by creating a large h value at the target to permit effective dispersion-matching, leads to an increasingly important intrabeam scatter heating mechanism as the beam cools, resulting in a minimum equilibrium emittance even in the absence of target heating and thus a minimum resolution. The prediction for the Cooler[6] is that dispersion-matching in 10 keV resolution scattering experiments is useful in increasing the luminosity for proton beam energies below about 100 MeV. At higher energies the beam current has to be reduced substantially to obtain the smaller emittance necessary to retain this resolution. In practice, therefore, a useful luminosity for the highest resolution experiments at energies above 100 MeV must rely on a narrow momentum spread in the cooled beam rather than on the dispersion-matching technique.

Minimum Emittance. The predicted equilibrium emittance in the IUCF Cooler at stored beam currents of a few mA should be about 0.1π in the absence of a target, about one order of magnitude better than the beam from our cyclotron.

Momentum Distribution. The electron cooling force is very anisotropic because of the flattened, disc-like electron velocity distribution after electrostatic acceleration. The longitudinal cooling force is stronger than the transverse cooling force and is highly non-linear. Whereas the transverse cooling is reasonably well represented by a single time constant for all ions in the beam core, the longitudinal force continues to increase in strength down to very small relative velocities. The magnetic confinement enhances the force in this low velocity region. As a result, the ion longitudinal momentum distribution must develop a very narrow "spike" at the momentum corresponding to the electron velocity. This narrow structure will be superimposed on a much broader component of the momentum distribution which will have a tail on the low momentum side from electron knock-on events in the target. A measurement of the second moment of the momentum distribution is not sufficient to exhibit this two-component structure.

Several effects can act to broaden the narrow momentum component. One such effect arises from a combination of finite emittance and the space charge depression in the center of the electron beam, which leads to off-axis particles being pulled toward different velocities on successive passes through the cooling region. Simulations[7] show that this effect may be expected to increase the width of the narrow structure to about 10 keV fwhm at 200 MeV for emittances above about $2\pi\cdot10^{-6}$ m. This emittance value is near the upper bound for a useful beam lifetime (of several seconds). So in typical experiments we expect the Cooler beam to be about one order of magnitude better in energy spread than the IUCF cyclotron beam.

A second effect is the influence of ripple and noise on the electron energy from power supplies in the electron system. The high voltage supply in particular must be carefully regulated to avoid momentum broadening from a time dependence in the mean electron energy.

If the full longitudinal momentum distribution were to become very narrow, the microwave instability arising from the induced image currents in the walls of the vacuum chamber would be expected to generate tails via a high frequency breakup phenomenon. The timescale is too rapid for stabilization by cooling. However the Landau damping caused by the presence of even a few percent of the beam within the broader component of the expected two-component momentum distribution should be sufficient to stabilize[8] the narrow component against microwave breakup. This implies that the presence of a target is necessary for the stable development of a two-component distribution and could explain the lack of supporting evidence from rings without targets to test the two-component picture. Experimenters are not used to targets making the beam quality better!

Expected Beam Quality. In summary, the emittance range to be expected in cooled target experiments with protons is between 0.1π, a lower bound set by intrabeam scattering in the strongly modulated beam envelope in the IUCF Cooler lattice, and about 2π, an upper bound set by loss lifetimes[9] with the thickest high Z targets when the beam emittance exceeds about 10% of the 25π Cooler acceptance. The second moment of the longitudinal momentum distribution will be somewhat smaller than the raw cyclotron beam, but with careful attention to electron beam power supply regulation, and in the presence of a target to generate a stabilizing tail against microwave breakup, we expect a much narrower second component or "spike" to appear in the momentum distribution which will make possible experiments of 10 keV resolution or better with currents of several mA. This expectation must be tested experimentally. Pion threshold phenomena offer a nuclear diagnostic technique for direct verification independent of detector resolution.

Beam Lifetime, Time Structure and Duty Factor

Cold storage experiments are cyclic. In each cycle the ring is filled, the energy may be adjusted, the electron cooling and target heating are turned on, and a period of data-taking ensues. The circulating current gradually diminishes due to interactions with the target and with residual gas. At some point the ring is reset to prepare for the next cycle.

Time Macrostructure. A series of simulation calculations for the Cooler[9] show that transverse losses, by multiple small angle scattering, bring the lifetime down to 5 to 10 seconds for a target at any of our three target stations if the equilibrium emittance is allowed to grow to 2π to 3π mm-mrad. Losses by multiple δ-ray knock-on events lead to a comparable longitudinal loss lifetime if the target contains about 10^{16} electrons/cm^2 ie about 0.1 to 0.2 μg/cm^2. Both effects are strongly non-linear in target thickness so it is misleading to present them in the form of loss cross sections. High resolving power waists at two of the three target stations give a third loss mechanism by dispersion coupling.

For an exponential decay with time of the stored beam current, it can be shown that if maximum luminosity is obtained by adjusting both the target thickness and the data-taking fraction of a complete time cycle, the optimal condition will be determined by the non-linearity[9] in the dependence of beam mean lifetime τ on target thickness d. If $\tau \approx d^{-n}$ and the fixed time for cooling and acceleration is t_o, then the optimal value of $u = t_o/\tau$ is the solution of the transcendental equation: $\ln(1+nu) = (n-1)u$, the optimal cycle time is simply $n\cdot t_o$ and the average current over a cycle is $1/(1+nu)$ while the duty factor is $\langle I\rangle^2/\langle I^2\rangle = 2/(2+nu)$. This leads to a macroscopic duty factor of 30-70%, and to a mean luminosity which about 20-50% of the peak luminosity, which occurs in each cycle when data-taking begins.

The lifetime depends on target Z, location, thickness, and on beam energy and ion type. Note that these optimal conditions, with cooling and acceleration times of about 3 seconds, lead to beam lifetimes in the range from 1 to 20 seconds.

Time Microstructure. Any rf time structure present in the beam from injection or acceleration is quickly lost while the coasting beam is being cooled. This absence of time microstructure is ideal for many coincidence experiments. However an rf cavity in the ring may be excited while cooling proceeds. In this case the beam will develop a tightly-bunched time microstructure at the rf frequency, provided the energy at the bucket center coincides with the energy defined by the cooling electron mean velocity. The increase in instantaneous current within these tight bunches will affect the beam stability. The upper limit due to the space charge tune shift is readily estimated. Other limits have yet to be established. The limit set by the transverse resistive wall instability, for example, is believed to lie[6] at several tens of mA.

By successive excitations of different rf systems of widely differing and harmonically related frequencies, interspersed with periods of cooling, it is possible to prepare a flexible range of time structures with pulse spacings ranging from a few ns to half a microsecond. Peak current limits may be expected to reduce the attainable luminosity at low microscopic duty factor relative to the maximum value which is obtained with a beam free of time structure. Part of the development plan for Cooler beams involves an exploration of phenomena limiting the peak current, so that experiment planning with pulsed beams can be based on harder information than is at present available.

Tails and Backgrounds

It is clear that the form of the phase space distributions is altered by the ring optics as well as by the cooling process. The familiar multiple scattering angular distribution and Vavilov energy straggling distribution, which are derived to cover the case of a single pass through a thick target may be considerably altered.

The finite ring acceptance leads to a "tail-cleanup" process by which the portions of the distribution near the aperture limits are preferentially eliminated, so that the edges of the distribution should be sharper and cleaner than is the case in a transport line. Simulations of the cleanup process by Monte Carlo techniques are made difficult by the low probabilities for the releveant processes for any individual particle. The form of the distribution at the intensity levels of order 10^{-6} of the peak density is not easy to establish. Yet these densities are important in determining effects such as background from apertures near the target location which may be of critical importance to the success of an experiment.

Historically, the development of extraction systems for circular accelerators was driven as much by the desire to reduce backgrounds as by the need for better detector access and control of beam parameters. The question of the extent to which internal target experiments in a cold storage environment may have a reduced background is a relevant concern.

An order of magnitude argument leads to an expectation of reduced background. Multiple passes through a thin target, with cooling to remove the deleterious effects of Coulomb interactions with the target nuclei and electrons, lead to a higher fraction of the beam undergoing the desired nuclear reactions than would be the case for a single pass through an external target with comparable luminosity snd good resolution. The efficiency of beam use, for a low Z target such as carbon, may approach 10% in the cold storage mode, in contrast to 0.01% to 0.1% with the external target. The generation of background from a beam dump is eliminated.

A closer examination shows that the loss from single Coulomb scatter on target nuclei generates comparable background in the two geometries. For an external target with beam dump, there are some scattering events that lead to background generated at the face of the beam dump. Introducing focussing lenses close to the target can reduce the flux striking the face of the dump, but replace it by background generated by scattered particles striking the face of the lenses. This background source, while weaker, is generally closer to the detectors, so the overall background may or may not be improved by trying to focus the beam into the dump. The slow neutron background emerging from a dump with a large entrance hole is replaced by a harder background component generated in the scattered beam interaction with the lens face.

In a cooled beam experiment, the quadrupole lenses downstream of the target are illuminated by the beam scattered through angles exceeding the acceptance cone and this is a significant source of background near the detectors which should be comparable to the background component from quadrupoles feeding beam into an external dump. Beam which is carried some distance downstream is less important and the location of all acceptance-defining apertures may be well away from the experiment, and may in addition be shielded if required.

A weak tail on the stored distribution which is able to strike a thick aperture near the thin target would be a serious background source. By ensuring that apertures near the target exceed the ring acceptance, the tails can be cleaned up at a distant point, and should not contribute appreciably.

A second source of background to be expected arises from residual gas interactions in the regions upstream and downstream from the target. Since the target is only a fraction of one microgram/cm^2, the relative importance of the gas in the vicinity of the target is much greater than in an external target geometry. The design of differential pumping apertures in a windowless gas target or vapor jet target experiment has to be carefully integrated with the detector design. If the apertures are all larger than the size determined by the ring acceptance, the clean edges of the distribution should give very little rate from the apertures. However, an attempt to build dynamically adjustable apertures which can be closed to reduce the pressure in the target vicinity after the beam is cooled must be accompanied by other variable acceptance-defining apertures elsewhere in the ring which are closed even further to keep the apertures near the experiment from seeing beam tails.

Project Status and Early Running Plans

The IUCF Cooler is in the middle of the component snd subsystem installation phase. The injection beam line magnets and ring dipole magnets are in place and are being connected to services and power supplies. The biggest assembly and installation task for the next six months is the eighteen ring quadrupole pairs, each pair on a common alignment fixture with accompanying hexapoles and steerers, diagnostic pickups and vacuum hardware. The electron system confinement magnetic elements (solenoids, toroids and steerers), and the high voltage platform for all the electron power supplies that operate at up to -300kV will also be being assembled in this period. We hope to achieve a rough ring vacuum and begin beam tests in the summer of 1987, with cooling system tests and a first experiment attempted by the end of 1987. This is a very tight schedule because the laboratory is at the same time attempting to maintain a full program of research with the cyclotron beams to serve the demands of its user community. It is possible that the constraint of finite resources, coupled with priority decisions not completely under the control of the Cooler working party, could stretch this schedule somewhat.

Beam tests can begin with the ring operating as a beam line in the one-turn-and-out mode made possible by the symmetry of the injection-extraction hardware. This beam can be obtained parasitically by splitting a time-shared fraction from non-Cooler users, a mode now in use successfully for spectrograph development.

The first experiments will use the simplest injection mode, by stripping, which requires acceleration to reach interesting stored energies. Beam rigidity will be limited at first to 3.2 T-m (about 400 MeV protons) to simplify ramping and to give time to condition the electron system to its full design voltage. The stripping mode will make all unpolarized ions $A \leqslant 7$ available. The sharing of beam with non-Cooler experiments will be of limited value in this early phase because the stripped beam rigidity is about 1 T-m, while most users require more energy.

When cooled beam experiments have demonstrated useful resolution, luminosity, and low backgrounds, the next stages of development will include the stacking injection mode, allowing time sharing of higher energy beams with non-Cooler users. Acceleration allows the cyclotron user to pick the beam energy, the Cooler operates as a synchrotron to give the Cooler user an independent choice of energy.

Operation with polarized beam is given a high priority because of the needs of the experimental program. An early demonstration will be attempted at low intensity to prove feasibility. When the stacking kickers are operational, the mode of slow stacking with cooling will be tried. Although this is limited in usefulness to experiments with beam lifetimes of minutes, a worthwhile program of polarized beam-polarized target experiments would be made possible by this mode.

The future plans may include operation with new ion sources, for example a pulsed positive source for raising the stored current, a negative polarized source for obtaining high current stored polarized beams with a short fill time, and possibly heavier ions from an ECR or EBIS source, the former being more useful if beams are to be shared with cyclotron experiments, the latter a better choice for ring filling.

After about a year of Cooler operation, enough information will have been established about the performance boundaries to decide whether, and if so when, the dual spectrometer system now being commissioned on a cyclotron beam line should be moved to a Cooler target station. The higher energies and better duty factor for particle-particle coincidence experiments will eventually make the Cooler the proper location. The ring has been laid out so that it can serve as a transport line with dispersion-matching so the spectrometers, after being moved, can continue to receive the direct cyclotron beam for users who require this option.

Summary

The IUCF Cooler is designed to serve a wide variety of needs of the intermediate energy user community. It will also be a test bed for study of the limitations of the cooled beam and internal target operation mode. The testing will begin in 1987, with unpolarized experiments in 1988, and with shared beam and polarized operation planned for about one year after startup.

The most valuable attribute of a ring with electron cooling may not be only the improvement in beam quality, although we expect the Cooler beams to be about an order of magnitude better in emittance and energy spread than the IUCF cyclotron beams. Rather the main benefit may be that it is a relatively inexpensive way to extend the energy range of beams in an existing laboratory without loss of beam quality.

The thin targets which are a necessity to obtain thermal equilibrium with the weak cooling force bring a number of side benefits to experiments, such as access to unperturbed recoil products. Thin targets do not imply reduced counting rates provided that stored beam intensities of several mA are achieved by one or more of the planned filling schemes.

Acknowledgement

The author is one of a group of more than fifty persons who have worked on the Cooler project since its inception. This is in fact a report of activities by all the members of that "Cooler working party".

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