STORAGE RINGS FOR CYCLOTRONS*

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Abstract

A number of storage rings are under design or being discussed as additions to existing accelerator laboratories. One such project is the IUCF Cooler, a light ion storage ring with electron cooling being developed as a research tool for increased precision in intermediate energy nuclear science. Some of the general features of ring designs and of the limitations to their performance will be reviewed, using the Indiana Cooler as an illustrative example. The status of the Cooler will be described.

Introduction

The cyclotron is a circular accelerator in which large longitudinal periodic electric fields add energy to a stored beam. The time of storage is short since the full energy is realized in hundreds to at most a few thousand turns. Other circular accelerators such as synchrocyclotrons and synchrotrons can store the beam for a longer time so that the final energy is reached with a smaller average accelerating force acting for a longer time. A storage ring may be thought of as the limiting case where, in the absence of energy loss mechanisms, the accelerating force may be reduced to zero and the beam may remain stored indefinitely.

A stored beam may be affected by small forces which are safely neglected during rapid acceleration. For example cyclotrons have been built in which integer and half-integer resonances are crossed during the acceleration. On the slower timescale on which synchrotrons operate, the cumulative effect of many coherent perturbations by the small force caused by a magnet misalignment or a quad strength error would not be tolerable. For long-term storage, much smaller effects due to resonances of sixth or higher order may be disruptive.

Not all small effects are detrimental. Frictional effects, which are often called cooling processes, although they may either cool or heat a stored beam during the approach to equilibrium, are examples of weak forces whose effects may become manifest only on a long timescale. Instead of energy changes of order MeV per turn as in cyclotrons, or keV per turn as in synchrotrons, the strength of a "cooling" force may be only of order eV/turn or less. To obtain a significant benefit from the action of such a force may require the beam to be stored for times of seconds or longer.

Non-conservative forces may be employed to change properties of a beam which are normally invariant. The beam brightness (number of particles per unit volume in phase space) may be increased for example by using a cooling process to reduce the beam emittance or energy spread, or both, while holding the number of beam particles fixed. The brightness can also be increased in a stripping process within a ring by adding new particles in the interstices of a dilute phase space. An increase in brightness can be exploited in principle to obtain a higher counting rate in an experiment of high resolution. Suitable manipulations of stored beams should improve the quality of measurements performed with them.

Just as beam confinement devices can be classified according to the size of the forces or the number of turns in which the force must continue to act to obtain a given result, such as an energy change or a change in brightness, it is possible to classify the geometries in which experiments with particle beams are carried out. A single pass through a fixed target into a beam dump is the analog of a one-shot accelerator such as an electrostatic or induction accelerator. If the particles are collected after passing the target, and recirculated for some hundreds of passes, we have the analog of a cyclotron. The target must be thinner so the dissipative interactions with electrons and nuclei in the target do not result in too great a cumulative deterioration of beam quality. During the recirculation, the average energy removed from the beam by interactions with target electrons may be restored. If the target thickness limit is set by the deterioration of quality of outgoing reaction products rather than that of the beam itself, the counting rate for a given experimental precision may be considerably higher than for a single pass geometry even though no cooling is employed.

Confinement for 10^3 to 10^4 revolutions allows slower processes such as synchrotron rotation in the longitudinal phase space (bunching or debunching) to modify the energy spread or the microscopic duty factor. The time scale can be understood by analogy to a synchrotron used as accelerator because the same forces of order keV/turn are involved.

If the target thickness in a beam recirculation geometry is reduced still further, the use of a cooling process such as immersion in a cold, co-moving intense electron beam may be employed to remove the heat introduced to the stored beam by target dissipative forces. For a certain range of energies and beam species, the resulting luminosity (reaction rate per unit reaction cross section) may be competitive to or even superior to that obtained in one-pass or few-pass experiments of comparable data quality (resolution, etc.).

Finally we can go to the limit of negligable force, which requires that the electrons be removed from the target nuclei. The target may be confined by a second storage device and we have the colliding beam experimental geometry, first used because of the gain in center-of-mass energy if the beams have opposite directions at the collision point, but also attractive in certain other applications.

The flexibility in beam manipulation which becomes available, once it is made possible to confine a particle beam for a a reasonably long time, has certain attraction to the experimenter. A number of accelerator labs are considering the application of rings for beam modification. Some of these rings are used primarily for duty factor adjustment. Others also incorporate cooling and internal target regions to make use of the recirculation mode. In the following sections are reviewed some of the factors which are common to the general problem of designing a useful storage device as a tool in nuclear science research.

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Limiting Phenomena

Cooling mechanisms: The emission of synchrotron light by ultrarelativistic beams in bending magnets is a stochastic process mainly of interest in electron and positron rings. Since photons are emitted in a narrow cone of half-angle $1/\gamma$ about the particle direction while energy is replaced by rf electric fields pointed in the direction of the equilibrium orbit, the net effect is a reduction of off-axis momentum components (transverse cooling). The quantum fluctuations lead to an equilibrium longitudinal momentum spread which is on the order of 1% of the beam momentum and therefore may be perceived as a heating process for an accelerator beam which is injected into the ring with a lower momentum spread. Timescales tend to be of order 10^{-2}s at the maximum energy for a given ring and increase rapidly if the energy is lowered.

An active network may sense the position of a beam particle, amplify the error signal, and feed forward to drive an electric field at the proper place and time to reduce the error. For a single particle with no amplifier noise, the error reduction timescale for optimum amplifier gain is on the order of a few turns. For a beam in which N particles cross the sensor/driver region within the response time, the gain must be reduced by a factor N, as otherwise the larger signal would cause an overcorrection and induce a coherent oscillation of all the particles. The cooling timescale for this stochastic cooling device thus is reduced in proportion to the beam intensity. The amplifier noise sets a limit to the lowest temperature reached at equilibrium for low intensity, while the confusing signal from other particles in the beam limits the minimum temperature that may be reached for more intense beams. A typical cooling time for a beam of order 10^6 particles can be about a minute. The technique has no restrictions on beam energy or particle type. It is now widely used in accumulation of antiprotons.

Immersion in an electron bath by passing the stored ions through a straight section in the storage ring in which an intense, cold electron beam is moving at the same velocity as the average ion can be viewed from the proper frame of the electrons. In this frame the ion is slowed and stops its motion relative to the electron bath via the low energy Coulomb interaction in much the same way as a charged particle is brought to rest in passing through matter. Timescales for electron cooling are of order 0.1 to 10 s. The technique has now been tested in the ion energy range from 1.4 to 203 MeV/amu. The IUCF Cooler is being designed for 500 MeV/amu while a test facility for intense 3 MeV electron beams is planned by an N.E.C./FNAL/Wisconsin collaboration to extend the technique to above 5 GeV. The limit is a technical one of dealing with the intense electron beam, with voltage-holding and with efficient recovery of the beam power.

The slowing of an ion beam in matter is usually considered as a heating mechanism, although this clearly depends on the relative width of initial and final velocity distributions. One application of note is in the slowing to rest of antiprotons obtained from LEAR by injecting into a cyclotron magnet operated with no rf but with a background gas of H_2 to slow the beam. The beam spirals into the center where stopped antiproton experiments can be carried out. The emittance can be smaller and the final brightness higher by this process than if an rf deceleration were used, because the stopping force reduces transverse velocity components whereas the use of decelerating rf would reduce only the longitudinal velocity.

Ion energy and mass range: What are the factors taken into account in the choice of a maximum target thickness for a nuclear experiment? Usually the energy change caused by the beam interacting with the target electrons is detrimental to experiment resolution and sets the target thickness limit. The product of target thickness and nuclear interaction cross section gives the efficiency of beam utilization. For one-pass experiments this is a quite small number, of order 10^{-6} to 10^{-4} at low to intermediate energies in experiments of good resolution.

At sufficiently high energy the energy loss rate is low enough in comparison to the incident energy and energy spread that the beam particles can all undergo nuclear interactions before the energy spread has become troublesome. This regime of high beam efficiency with very thick targets occurs above some tens of GeV/amu. Essentially every beam particle can undergo at least one nuclear interaction. The energy resolution is given by the energy loss for a minimum ionizing particle in a target of thickness of order 10^{24} nuclei/cm^2 and is some hundreds of MeV.

In a recirculation geometry, the presence of other beam interactions with the electrons of target atoms may have to be taken into account. For example, charge-changing collisions may lead to a loss of the ions from the circulating beam. The loss rate by charge-changing can be compared to the rate of nuclear (presumably useful) processes to define an efficiency of beam utilization, in this case based on the ratio of nuclear to charge-changing cross sections. By comparing this efficiency with the one-pass efficiency given above which was based on energy resolution criteria, it is possible to divide the mass-energy regime into a region where multiple pass experiments operate with higher efficiency than single pass experiments. Using the systematics of one-electron pickup cross sections for fully-stripped beams as compiled in Figure 1, we can deduce that the dividing line for a beam of energy E and atomic mass A on a target of equal mass is located at approximately E/A > 2A MeV/amu. Above this dividing line it is possible to obtain higher luminosity by recirculation after injection into a storage ring than by single pass usage.

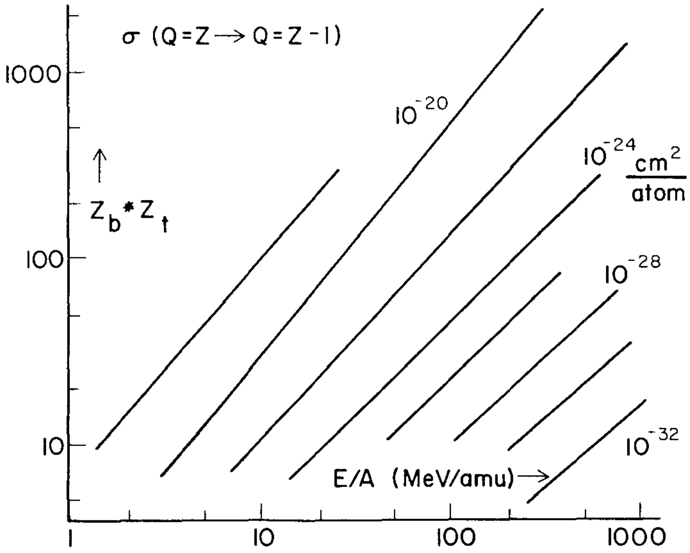

Figure 1. The systematic relation of single electron pickup cross section to E/A and the product Z_bZ_t of beam and target atomic numbers. The data is gathered from a variety of experimental and theoretical sources a representative sample of which are given in ref. 1. The parameter is the cross section per atom in cm^2.

Small Waists in Long Straights?

An external beam line can shape the ion beam to match the needs of the experimental apparatus. The size of the beam spot on target, for example, may be matched to the spatial resolution of the detector. Dispersion matching may be used to improve the resolution.

An internal target experiment has similar needs. The extent to which these can be met by a realizable ring lattice design is a central issue in defining the regime in which the stored beam experiment has better performance, judged by some objective criterion such as the achievable luminosity for a given resolution, or by signal-to-background ratio, or by some other measure of data quality.

One of the goals of the IUCF Cooler design has been to prepare a beam for an internal target for a high resolution spectrometer. To allow the spectrograph to measure cross sections over a reasonably wide angular range, the length of the straight section has to be comparable to the size of the spectrometer. A clear drift of about 3 meters on either side of the target allows the spectrometer to take data at lab angles of a few degrees.

The lattice parameter at the target which determines the resolving power for a given emittance is the value of $\eta_x/\sqrt{\beta_x}$, where η_x is the dispersion and β_x is the aperture function at the waist, both measured in the common bend plane of ring and spectrometer. This resolving power parameter can be made larger only by increasing the value of β_x in the bending magnets of the ring. The bends are strong horizontally-focussing lenses, so that a large β_x in the bend increases the chromaticity (the rate of change of tune with momentum spread), and thus reduces the momentum acceptance of the ring. Target interactions generate a momentum tail which must be contained to have a stored beam lifetime that exceeds the cooling time. A minimum momentum acceptance of order 0.3% is necessary.

While it is possible to cancel some of the chromaticity by families of hexapoles, there is an upper limit to the strength of these non-linear elements beyond which the cumulative effect of higher order and cross terms reduces the transverse acceptance below the value necessary for a useful lifetime for single scattering losses. While the optimum compromise is sensitive to factors such as the target Z and various lattice details, the general principle is that there is an upper limit to the value of the resolving power parameter. A given resolution is then obtained by cooling the beam transversely until the emittance is small enough.

The IUCF Cooler design of one year ago[2] had values of β_x in the dipoles and on target of 150 m and 0.1 m respectively. When the large chromaticity was set to zero and the higher order effects were explored with the help of the particle tracking program PATRICE[3], it was apparent that the hexapoles were too strong. The decision was made to reduce the β modulation in both transverse planes by an order of magnitude, using β_x= 50 m and 0.3 m at magnet and target respectively. This serves to reduce the chromaticities by a factor of three so that the necessary minimum momentum acceptance can be achieved without the use of non-linear elements. The option to increase the resolving power at the spectrograph target by a variation in quad strength is retained, to allow the exact limit to be determined by experiment once the ring is in operation. The relative magnitude of transverse to longitudinal loss rates depends on the target atomic number so the optimum β_x will differ somewhat for different targets.

A simple model helps to illustrate the relation between sensitivity to momentum changes, the size of a target waist, the length of the drift and the beam size in the focussing lens. Consider a cell consisting of a thin lens of focal length f between two equal drifts of lengths s. The transport matrix M is formed from the product of the matrices for the three elements:

$$M = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix} \quad \text{where} \begin{pmatrix} x' \\ \theta_x' \end{pmatrix} = M \cdot \begin{pmatrix} x \\ \theta \end{pmatrix}$$

To make a periodic structure from these cells, we must relate the output to the input by the requirement that each cell gives a phase advance ϕ and waists β_1 and β_2 at drift midpoint and lens respectively:

$$M = \begin{pmatrix} 1-s/f & 2s-s^2/f \\ -1/f & 1-s/f \end{pmatrix} = \begin{pmatrix} \cos\phi & \beta_1 \sin\phi \\ (\sin\phi)/\beta_1 & \cos\phi \end{pmatrix}$$

We have used symmetric cells to avoid intrduction of the other Courant-Snyder[4] parameters. Solving for $\cos\phi$ and β_1 yields:

$\cos\phi = 1-s/f$, with stability limits $0 \leqslant s/f \leqslant 2$, and

$\beta_1{}^2 = s.(2f-s)$. The value of β_2 is found by the change

in β in the drift: $\beta_2 = \beta_1 + s^2/\beta_1 \rightarrow \beta_1 \cdot \beta_2 = 2fs$.

These equations show many of the main features which appear in a more complicated ring design. A small β_1 requires working very close to the stability limit where the phase advance per cell is just below π. A small decrease in f would then make $\cos\phi < -1$. The focal length of a thin magnetic lens is proportional to momentum so the momentum acceptance is clearly bounded on the low side. A small β_1 makes the value of β_2 large. The chromaticity, given by $-N\beta_2/4\pi f$, where N is the number of cells in the complete ring, is also large. This is an alternative language for expressing the momentum sensitivity in terms of the distance from the nearest resonance and the first derivative of the change with momentum.

To mock up the Cooler momentum sensitivity by fitting the parameters of this simple model to the actual design, we note that the β product gives $s \cong 4$ m $f \cong 2$ m, and for a choice of β_1= 0.1 m, the unstable momentum differs from the design momentum by less than 0.07%. Increasing β_1 by a factor of three is barely enough to achieve the design goal of ±0.2%.

If a unit cell with both focussing and defocussing elements is used, to mock up the alternating gradient situation for quadrupole lenses, the sensitivity to momentum changes is increased. Stability may be obtained only within a band of momenta with unstable regions on either side.

While small β straight sections have been designed for intersecting storage rings, the peculiar requirements of low β, long drift, high resolving power and dispersion which are part of the design problem of incorporating a spectrometer experiment into a cooling ring will need considerably more attention before it becomes clear what the ultimate limit to performance will be.

Momentum Distributions

Beam particles in a cooler ring with internal targets make repetitive passes through the target material, the cooling region, and the electromagnetic fields of the confinement lattice, and perhaps also through devices such as rf accelerating structures. The usual treatment of the response of the beam to the interaction with a target in a single pass, which leads to a multiple scattering distribution for the transverse momentum arising from Coulomb scatter by target nuclei, and a Vavilov distribution for the longitudinal momentum arising from Coulomb scatter by target electrons, must be modified because of the presence of cooling and confinement forces.

The simplest case to consider is the longitudinal momentum of an unbunched beam confined in a time-independent magnetic field. If the target thickness and the cooling force are both independent of the transverse coordinates, the problem becomes one-dimensional, with momentum conserved in transport between target and cooling device. The only effect of the confinement lattice on the distribution is to introduce a loss mechanism which throws away particles that exceed the ring momentum acceptance. This case has been treated[5] by a Monte Carlo calculation using a realistic electron cooling force[6] for the IUCF Cooler. An ensemble of 10^3 particles followed through about 10^6 revolutions. The first results of this procedure show clearly that:

a) to obtain a reasonable lifetime, the ring momentum acceptance must exceed the maximum momentum that can be transferred to a target electron in a single knockon collision by a factor of two to three;

b) the lifetime becomes short if the target is thick enough that the average energy loss per revolution exceeds the average energy added back in passing through the cooling device. The thickness limit (about 50 ng/cm^2 for H_2 and 100 ng/cm^2 for other target materials in the case of a beam of 180 MeV protons) is within a factor of two of the value predictable by "handwaving" arguments;

c) the momentum distribution consists of a very sharp peak and a tail of roughly 1/p shape on the low energy side. The peak width is determined by the velocity spread of the cooling electrons and is on the order of 1 keV;

d) as the target thickness is increased, the area under the sharp peak is reduced but the width of the peak is hardly affected. This is in sharp contrast to uncooled passage through a thick target where the target thickness determines the peak width. A "thermal runaway" occurs when all of the particles have been shifted to the tail and the sharp peak is about to vanish;

e) if the initial distribution is a Gaussian of width given by the measured cyclotron beam resolution at injection into the ring, and the target is set to zero thickness, the beam all moves into the sharp peak with a time constant of 0.11 seconds;

The extension of this calculation to the two Hamiltonian conjugate longitudinal dimensions to study the effect of rf acceleration is contemplated to see if the rapid longitudinal cooling can be used during the stacking phase at injection to increase the stored beam intensity.

Target Phenomena

The stored beam intercepting an internal target constitutes a strongly-coupled system in which there are a number of effects that must be taken into consideration in the planning of an experiment. Some of these are familiar and may be treated by analogy with external one-pass targetting. Others may be less intuitively obvious. A list of these with brief descriptive commentary may be of interest.

Heating of Beam by Target.

a) Longitudinal. The electrons in the target cause both a loss in energy and an increase in energy spread of the beam. The shape of the resulting distribution is strongly modified by electron cooling. See earlier discussion.

b) Transverse. The target nuclei deflect the beam particles by small angle Coulomb scattering. The electron cooling modifies the distribution so that the usual multiple scattering treatment is not applicable.

c) Dispersion-Coupled Transverse. An energy loss of a particle on the equilibrium orbit at a point where the dispersion is large will induce a betatron oscillation, resulting in an increase in the transverse temperature. There is a correlation in the full phase space such that if the exact amount of energy lost were to be added back at a carefully selected point downstream, eg. by an accelerating cavity placed an integer number of betatron wavelengths downstream in a region having the same dispersion as the target, the coupled heating could be cancelled. Because of the statistical nature of the electron collisions giving rise to the energy loss, however, it is at best possible only to reduce the magnitude of the effect. The long tail from knockon electrons will generate a transverse tail on the beam which is not helped by adding back the much smaller average energy loss per turn.

Heating of Target by Beam.

a) Vapor Jets. The material heated by the beam is swept away rapidly enough that the target temperature is little affected by the beam. A cluster jet however may give the appearance of heating as evidenced by a beam-intensity-related rise in the pressure in the target region. This effect[7] is apparently caused by ionization of target clusters leading to Coulomb fragmentation and a loss in collection efficiency of the jet material by the pumps.

b) Doppler Luminosity Limit. If a spatially-localized target such as a fiber or whisker is being used, the heat supplied to the target by the average energy loss rate of the beam is directly proportional to the luminosity. The situation is only different from external single pass targetting because the geometry of the target may change the amount of heat which can be carried away at a given target temperature. If, for example, the main heat transfer process is by radiation, as in the case of a carbon fiber, the radiating area is proportional to the circumference of the fiber rather than the beam spot width. In a very high resolution experiment, the nuclear motion due to the elevated target temperature may contribute significantly to the experimental energy resolution, so that the maximum luminosity is limited by heat transfer considerations. One example[8] has been worked out showing that a luminosity of nearly 10^{33}/cm^{2}s may be possible for 150 MeV protons on a carbon fiber of 3 10^{-6} m diameter with 7 keV resolution and an acceptable fiber evaporation rate.

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Lifetime Limitations.

a) beam loss caused by target heating. The three effects mentioned above as contributing to beam heating by the target can each also lead to a mechanism for beam loss, and to a reduction in the storage lifetime. The longitudinal and transverse Coulomb scattering, by electrons and nuclei in the target respectively, lead to tails which may lie outside the acceptance of the storage ring. A large angular acceptance at the target reduces the loss rate for single large angle Coulomb scatter events, while a momentum acceptance much larger than the knockon electron momentum transfer reduces the longitudinal loss rate. For a target in a region of high dispersion, a beam particle may lose enough energy in a single electron knockon event that the induced betatron oscillation amplitude lies outside the ring transverse acceptance. To obtain an acceptable lifetime may impose a constraint on the properties of the target waist equivalent to an upper limit on resolving power.

b) beam loss caused by charge-changing. A fully-stripped beam can pick up an electron from a target atom. Ions with electrons can gain or lose charge. The ring is not normally designed to contain more than one charge state although this is possible in principle[9]. This loss mechanism sets a lower bound to the energy range, for useful internal target experiments with cooling, for a given beam and target combination. A figure showing the trend of the single electron pickup cross sections was given above. Note that even a proton beam can have a measurable rate of neutral production in a heavy target. This process can form the basis for a useful absolute luminosity monitor at not too high energies.

c) target loss by evaporation. The elevated temperature caused by beam heating may lead to an appreciable evaporation of a fiber target so that the limiting luminosity may be set by the rate of material loss.

d) target loss by burnup. The small number of nuclei contained in a fiber target, or in a separated-isotope coating applied to such a fiber, means that an experiment with high integrated luminosity may use up a significant fraction of the target material through nuclear interactions.

e) target loss by radiation damage. Before a complete nuclear burnup of the target material has occurred, the structural damage caused by the extremely high radiation dosage to a limited amount of material may cause a physical disruption. The target mounting method should allow for a feed mechanism to bring fresh material into contact with the beam. A coating applied to a fiber surface may separate from differential thermal or radiation-induced expansion.

f) target loss by coherent beam displacement. If a fiber target is located to the side of the beam distribution rather than at the point of peak intensity, a small displacement in beam position, caused for example by power supply ripple on the ring magnet fields, can result in a modulation of the power supplied to the fiber. The thermal time constant can be less than 10^{-4} s, so the temperature limit must be applied to the peak rather than the average luminosity.

Beam Instability Driven by a Gas Target.

The positive ion cloud left behind by the ionization in a gas target by an intense beam has inertia. A beam moving from left to right for example leaves behind a charged cloud which pushes to the right and can add energy to the motion in selected coherent betatron patterns. The effect is most serious for a small beam size at the target and for low beam energies which ionize heavily and react to the ion cloud more strongly. Feedback may be useful to stabilize the lowest mode.

Quasi-Ergodic Runaway.

If a beam particle lies on a trajectory passing once through a spatially-localized target such as a fiber, the quasi-ergodic hypothesis of statistical mechanics argues that the trajectory will pass again through the same region of phase space so the target will be struck again and again by the same ensemble of the beam particles rather than by all particles with equal probability. The modifications to the argument caused by cooling, target heating, etc. do not change the practical consequence that it may be difficult to keep a given particle, having once struck the target, from striking it again for a sufficiently long time that the slow cooling process can undo the changes caused by the first passage. In an extreme case the target can deplete the beam distribution of the portion of the beam which is able to strike the target. The beam which remains is that portion which is unable to reach the localized target, so that the luminosity drops to a low value. It is important to arrange enough mixing among the particles in the beam so that all particles have a comparable chance to pass through the target, and so that the amount of material encountered by any particle, averaged over the cooling time, causes no more heating than can be carried away by the beam cooling device.

IUCF Cooler Project Status

Authorization for construction was received in April 1983, both for the State of Indiana-funded building addition and for the National Science Foundation-funded Cooler ring and ancillary equipment. The building design was frozen in June 1983 and groundbreaking occurred in October 1983. Estimated construction time for the building is about one year.

The Cooler ring is in the intensive design and procurement phase for the major hardware components. Bids have been received for the lattice magnet power supplies, the coils for these magnets are out for bid, while the detailing of the magnet steel and supports is underway. Ordering of most of the vacuum pumps has been initiated, including some of the large pumps for the differentially-pumped jet targets. A high voltage test stand is in operation to explore the behavior of the cooling electron acceleration tube assemblies at 275 kV and to fix the inside diameter of the solenoids that will surround the electron gun and collector.

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Diagnostic techniques for stored beams are being developed during the running in of the low energy storage ring[10] reported elsewhere in these proceedings. The beam splitting hardware which allows time-sharing of cyclotron beams between the intermittent Cooler ring-filling task and other users has been designed and is being fabricated and installed piecemeal to minimize interference with ongoing operation. We hope to offer split beam operation to two simultaneous users in the present building before the end of 1984. The transfer line optics for the beam line extension to the Cooler are complete and the purchasing of the dipoles, quadrupoles and power supplies for the beam line has been initiated. Shielding roof beams and wall blocks are on order.

About 13 full-time-equivalent persons are now involved in the Cooler construction from a pool of nearly 40 persons whose work is shared between the Cooler project and other laboratory activities.

The present schedule calls for installation work reaching peak activity level during 1985, first beam tests during 1986 and first nuclear experiments in 1987.

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