IUCF COOLER RING STATUS 1989*

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Summary

The IUCF Cooler is a synchrotron-storage ring with electron cooling. The construction was funded in 1983 with beam tests beginning in 1987. Following a year of commissioning, the ring is beginning to provide beams for research users. This paper reviews some of the recent accomplishments and summarizes some of the operating characteristics as presently understood.

Introduction

The Indiana University Cyclotron Facility (IUCF) is a national user facility in intermediate energy nuclear science operated by Indiana University and supported primarily by the U.S. National Science Foundation. The 2 Tesla-meter isochronous cyclotron of IUCF provides beams of atomic mass $1 \leqslant A \leqslant 7$. The proton kinetic energies range from 12 to 215 MeV, with about 2/3 of the running time devoted to polarized $^1H^+$ and $^2H^+$ operation.

The IUCF Cooler is both an additional accelerator and a research instrument. The unconventional lattice [1] leaves an unusually large fraction of the ring circumference open for internal target experiments. The introduction of target material into the stored beam path modifies the form of the phase space distribution [2] in equilibrium with electron cooling. The ring operators must work closely with the experimental users in establishing mutually acceptable running conditions.

The present report reviews several aspects of machine operation after a few months of experience, and summarizes the current status.

Capsule History

In 1979 the electron cooling experiments at CERN and FNAL, confirming the earlier results from Novosibirsk, and the announcement of the LEAR project started us thinking about possible application of the new technology of stored, cooled beams to nuclear physics research at intermediate energies. A construction proposal for the Cooler received favorable reviews in 1981 and was funded beginning in 1983. A new building addition to house the ring was occupied in 1985 and first hardware began to arrive. By the summer of 1987 installation had reached the stage that a beam could be injected into the first section of the ring. A stored beam was first observed in the autumn of that year.

In 1988, acceleration of a stored beam and storage again at a higher energy was achieved in February. An internal gas jet target and detector array began operation in March, and electron cooling was first observed in April.

In the first few months of operation, the injection method used was the stripping of a 90 MeV H_2^+ ion beam. After filling, the closed orbit in the ring is displaced by turning off a set of bumper dipoles to drop the internal beam below the stripping foil edge for storage.

In May 1988, a first ferrite kicker became operational, and a single turn of polarized protons was stored and cooled. A first low-statistics observation of polarization in a stored cooled beam of 179 MeV protons was made in July. The second kicker was available by the end of 1988, permitting a localized displacement of the closed orbit at the injection septum, and it was demonstrated that repetitive firings of this matched pair of full aperture kickers did not destroy the stored beam. With the addition of control hardware and software, rf stacking of polarized beam was possible for the first time in March 1989, and was immediately used for a first definitive study of the effect on beam polarization direction of solenoids in the cooling region.

The precession by the cooling solenoidal field of beam spin may be reduced by fields of opposite sign from a pair of shorter, stronger "compensation solenoids" mounted in the same straight section. Any deviation from exact cancellation of the solenoidal fields acts as a partially-excited Siberian snake, and its influence on the components of the beam polarization vector in the vicinity of an intrinsic depolarization resonance (in this case $G\gamma = 2$) is of some interest. The data from this recent run are in analysis and will be reported elsewhere. More details of the various injection modes into the Cooler are presented later in this report.

Beam Species and Energies

From a much longer list of ions that will eventually be available, we have stored and cooled protons at seven energies from 45 to 287 MeV and polarized protons at three energies from 120 to 179 MeV. A beam of $^3He^{++}$ nuclei of 44 MeV has been stored and cooled. In addition, deuterons and $^3He^+$ ions have been injected and completed one turn, but not yet stored. To this date only unpolarized protons have been accelerated.

H_2^+ molecular ions of 90 MeV have been stored but with the present average ring pressure of 3 nTorr, the 0.1 s lifetime is slightly too short for useful cooling. The effect of the electron beam on neutral H^0 production by dissociation of the H_2^+ ion has been observed (see later in this report) and does not appear to preclude cooling this beam once the lifetime has been increased by the next round of vacuum improvements.

*Work supported by the U.S. National Science Foundation under grants NSF PHY 82-11347 and 87-14406.

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Injection Modes

The injection system of the IUCF Cooler is designed for injection either by stripping or kicking. It is easy to switch between these modes during a run by adding or removing the stripping foil and retuning a few magnets. Rf stacking in the longitudinal phase space and multiturn (in our case more correctly fewturn) injection by betatron motion in the transverse phase space are methods to increase the kicked injection intensity. For all of these modes, cooling while injecting can give rise to slow accumulation of higher stored currents by overcoming the phase space density constraints of the Liouville or brightness theorem.

The stripping mode is particularly simple to implement and was employed for the first ring studies. An H_2^+ ion of 90 MeV strips on average to 1.8 protons of 45 MeV (magnetic rigidity 0.98 Tesla-meters and orbit frequency in our ring of 1.03 MHz). We find at best 1.4 protons/ion after 1/6 turn, indicating about 80% transmission through the injection apertures. An optimized setup with 0.3 μA of cyclotron beam gives 0.15 mA stored after stripping for a current gain in the stripping process of about 350 turns. Another factor of three should be obtainable with full use of the ring acceptance.

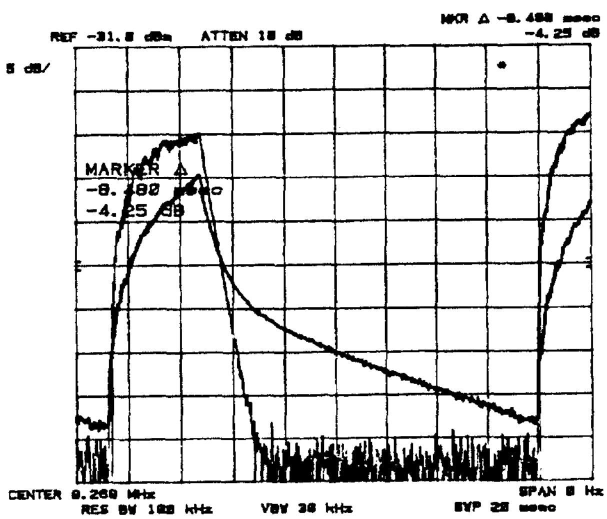

Figure 1. The time dependence of circulating beam intensity on a log scale while using stripping injection at 60 Hz repitition. The current grows for about 3 ms while a beam gate in the cyclotron switchyard admits beam to the Cooler. The incoming beam is then switched off, and the stored beam decays with about 8 ms lifetime. The more rapid initial decay is interpreted as loss of particles from the outer fringes of the phase space distribution and may be minimized by more careful tuning. The lifetime is normally increased to a much greater value by moving the closed orbit off the stripper foil at the end of the filling interval. This plot shows our first beam in November 1987, before the bumpers were available. The "bumper" triplet, used to move the stored beam off the foil, employ 1 kV power transistors to switch off the current, giving a field which drops in < 1 ms. The yoke material is Corovac, manufactured in West Germany.

If the bumper waveforms are carefully matched, the stored beam perturbation is local. With a proper choice of matched bumper amplitudes, a stored and cooled beam can be moved close to the foil while maintaining a long lifetime. Beam injected by stripping then has appreciable betatron amplitude which can be damped by cooling before the cycle is repeated.

The first observation of cooled accumulation while stripping was made in January 1989. The process has been exploited to reach stored and cooled proton beam currents of 0.35 mA, permitting exploration of the onset of instabilities and other collective phenomena. The process of slow cooled accumulation has also been observed with $^3He^{++}$ beams injected by stripping of 44 MeV $^3He^+$ from the cyclotron, as shown below.

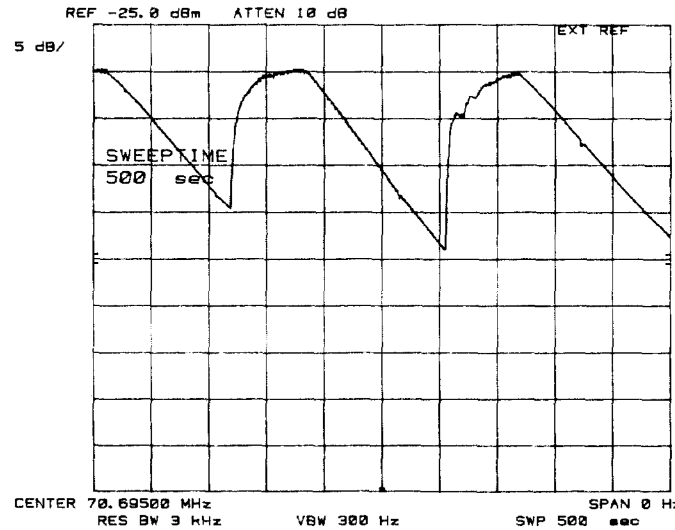

Figure 2. Slow accumulation of $^3He^{++}$ by cooling while repeating stripping injection cycles. The horizontal scale covers 500 seconds. The vertical scale is the logarithm of rf signal from beam cooled into buckets on the 13 th harmonic of the orbit frequency but observed on the 117 th harmonic. (Cooled beam bursts are very narrow in time and are therefore rich in higher harmonic content.) Bumper operation is halted at 10 s and again at 370 s, and left dormant for a couple of minutes, long enough to measure the 61 s beam mean life. When repetitive filling is resumed, the intensity recovers in 30 to 50 seconds. The irregular second refilling is caused by two brief intervals of reduced cyclotron intensity. The accumulation mode averages nicely over such fluctuations. Beam currents of about 30 μA were being obtained at the time this picture was made.

At 180 seconds, incoming beam is interrupted by inserting a stop in the injection line while the bumpers continue to fire. The lifetime is only 54 s in this situation because the beam spends more time very close to the foil edge. In the original of the figure, this exponential decay curve, obtained with the bumpers firing at 0.6 s intervals and no incident beam, is seen to be made up of a staircase of small steps.

Note the occasional drop of signal strength during the decay phase, followed by full recovery, showing that no beam has been lost. The beam at this instant develops a coherent synchrotron oscillation which is damped by cooling. The temporary reduction in high harmonic content is observed. The origin of the perturbing signal is unclear.

Cooled accumulation is of particular interest in conjunction with future experiments employing very thin polarized targets, where very long lifetimes allow good duty factor even if a minute or two is taken up with refilling.

Stacking injection employs repetitive kicker firings, on a 20 to 100 ms cycle, with each firing injecting one turn (or a few turns) of beam from the cyclotron. The Cooler rf cavity is raised to an amplitude of about 1 kV and phase-locked to the cyclotron prior to each injection pulse into the center of a synchrotron bucket. The amplitude remains high for the order of 100 µs to make a 90° debunching rotation, then dropped to about 30 V. The phase lock is removed, a deceleration takes place by sweeping the frequency downward by about 0.2% (half the momentum acceptance). Because of the large ratio of dispersion to beam width at the injection point, this deceleration displaces the beam by a sufficient amount that the next kicker fire will not throw the stacked beam back into the septum. At the end of the deceleration ramp the rf amplitude is switched off so the beam is left at the stack momentum, and the rf frequency is returned to the match the cyclotron for the next cycle. While all this is going on the kicker coaxial lines are recharging for the next pulse.

This whole process has been in development over the past six weeks, and has recently succeeded in accumulating a few cycles for use in the beam polarization measurement mentioned above. A view of the overall experiment cycle as seen by a spectrum analyzer tuned to the frequency after deceleration is shown below. The stacking process is described in more detail in an accompanying paper [3].

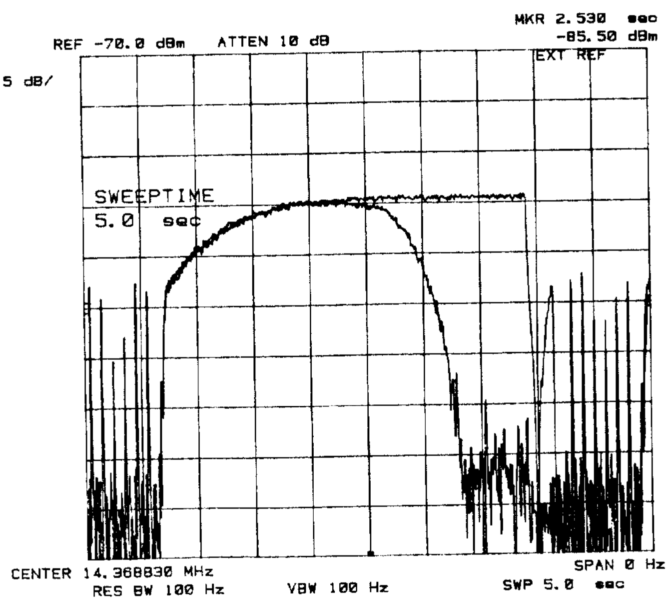

Figure 3. Signal from a stacked polarized beam. The complete cycle in this case was 4.2 s, consisting of 6 stack cycles of 0.1 s period each, followed by adiabatic capture and about 1.1 s for cooling. The experimenters then took over the timing and moved the beam onto a carbon target taking asymmetry data between 2.3 and 3.3 s as the beam was used up. The double exposure shows the same cycle with the beam not moved onto the target and the intensity flat until 3.9 s when a switch back to the stacking synthesizer took place in preparation for the next cycle. The lifetime measured for 120 MeV protons during this run was 22 min.

The stacking process is visible as a brief spike of beam signal from the beam in the small deceleration bucket while the rf is left on for 5 ms at the end of each deceleration ramp. The gain in intensity from 6 stack cycles is estimated to lie between 2 and 3 on this first use of the process. We anticipate gains of 30 to 50 with a few hundred stack cycles and further optimization. Gains from transverse multiturn and cooled accumulation have not yet been observed.

Acceleration

The IUCF Cooler is designed to accept any beam the cyclotron can produce, to accelerate it to any energy up to a maximum magnetic rigidity of 3.6 T-m, and there to cool it and make it available for internal target experiments. The lower energy limit is less well-defined, but is nominally set at 0.5 T-m.

The time taken to accelerate is chosen comparable to the cooling time, and is limited to 30% of full scale current/s by the ring dipole energy storage and the over-voltage available from the dipole power supply. We have been ramping routinely at 0.5 T-m/s, which is about half the eventual rate. The ramp is calculated as a sequence of slope-endpoint number pairs, loaded into memory on each of 96 function generator cards. This gives the flexibility to allow a different non-linear function for each ramping device in the ring. After a ramp is calculated and down-loaded, the control computer has only to issue a start command. Each card then carries its associated power supply (or synthesizer in the case of the rf frequency) from the initial value, at which the device has been set for injection, to the final value corresponding to an freely chosen higher energy.

The first and last few vectors define a smooth start and stop between which the chosen ramping function is linear in (Bρ). Devices that begin to saturate have increasing slope as the ramp proceeds, calculated automatically from mapping data. Relativity causes a decreasing slope for the rf frequency. An on-line editing facility allows a selected vector table to be altered (or restored to the unaltered state) by the operator in response to information from the beam. An example is the beam position in dispersed regions which can signal a mismatch between rf frequency and dipole field, or the ring tune determined by knockout during the ramp, which can indicate a problem with quadrupole scaling. The use of active feedback during ramps has been avoided so that ramps can be developed with easy beams of high intensity and good visibility, and then used with no performance deterioration for more difficult beams.

To date we have accelerated and stored proton beams of the following energies: 65, 108, 120, 148, 169, and 287 MeV. Each of these energies is required for a particular approved experiment except for 169 MeV, which is twice the rigidity of the stripped proton beam, and was used to provide a good ring setup before injecting H_2^+ ions. All of these energies except 65 MeV have been electron-cooled. Direct kicker injection without acceleration has provided polarized and unpolarized cooled protons of 120, 148, and 179 MeV, so with the $^3He^{++}$ and H_2^+ ions and 45 MeV protons used for injection mentioned earlier, we have developed 10 different beams in the past 13 months. The range of rigidities explored extends from 0.83 to 2.63 T-m.

The main difficulty with the ramping process after an initial debugging period has been poor reproducibility in the intensity transmitted through the first 0.1 s of the ramp. We have traced part of this to a sensitivity to the way the phase space is populated by stripping injection, which is affected by small changes made by the cyclotron operators during a run. There is also observed an intermittent coherent synchrotron oscillation, although the ramp start should be gradual enough to be adiabatic for longitudinal motion. This effect may be associated with the phase-unlocking operation, now under study. With the best conditions 20 to 50 % of the beam can be carried to the higher energy but full transmission has yet to be seen. The use of cooling prior to acceleration makes the process much less sensitive to small variations and immune to changes in the phase space distribution after filling. At this time the control system allows cooling either before or after acceleration but not both. Provision for the cool-ramp-cool mode, and for more flexible tailoring of the ramp start are now high on the list of control improvements for the near future.

Electron Cooling

To cool the highest energy protons which can be stored in the IUCF Cooler requires electron kinetic energies up to 270 keV. The electron system has provided beams of this energy in tests in the autumn of 1988, and has cooled a stored beam with electron energy of 156 keV (protons of 287 MeV). This appears to be the highest energy at which electron cooling of a stored beam has been observed to date.

The cooled beam develops a very narrow momentum distribution. This can be observed indirectly but easily with the rf cavity excited. Beam then is cooled to the vicinity of the stable fixed point in longitudinal phase space, and the momentum spread can be inferred from the observed time spread. With no rf cavity excited, the beam coasts, losing all time structure, and if the intensity is neither too low nor too high, the incoherent (Schottky) noise from passage of the individual particles through a beam pickup is a measure of the frequency spread that is then easily related to velocity and momentum spread.

If the intensity is very low, signal averaging techniques are needed to examine the Schottky spectrum. The observed distribution may be broadened by slow drifts in the electron energy via varying space charge neutralization. If the intensity is too high, the well-known Schottky noise suppression and peak splitting can occur, indicating the onset of collective phenomena, as the assumption that beam particles move independently breaks down. An example of the latter is shown below.

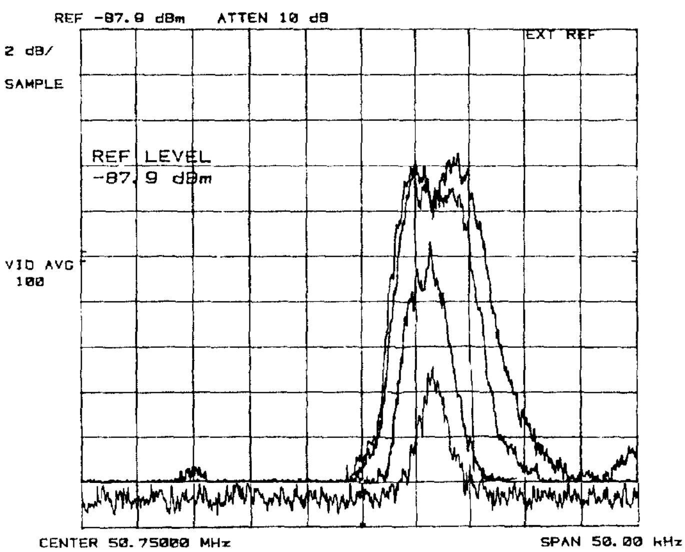

Figure 4. Successive Schottky spectra of a coasting $^3He^{++}$ beam as the stored current is reduced by beam loss through electron pickup. The highest peak is observed with slow accumulation in progress and shows weak satellites near the edges of the picture, probably artifacts of the filling process. After filling stops, the peak doubling persists, then disappears at lower intensity. The narrowest peak is $6 \cdot 10^{-5}$ fwhm (-3db points). Typical proton widths are narrower. [5]

The measurement of the properties of the cooling force is an ongoing activity at the IUCF Cooler that will be described in greater detail elsewhere [4]. An insulated cylinder surrounds the electron beam within the cooling region solenoid. By connecting this cylinder via a vacuum feedthrough to an external power supply, it is possible to modulate the electron velocity. This procedure has been used to correct for residual ripple on the electron high voltage power supply, giving an increase in the steepness of the longitudinal force-velocity profile by a factor of about two. A Faraday induction spiral was mounted in the ring in January of this year. This provides a flux change of up to ±0.4 Weber that can be used to change the energy of a coasting beam, or to compete with the cooling force as a cooling diagnostic aid. For example, the ripple cancellation test used the frequency shift of the cooled Schottky peak as the Faraday acceleration voltage alternated in sign to extract the shape of the interior part of the nonlinear force-velocity profile.

It was observed during these measurements that if the Faraday voltage was made too large, the lifetime of the cooled, coasting beam was reduced. The competition of the cooling force with the induction emf leads to both a stable and an unstable fixed point. The Schottky peak marks the position of the stable fixed point. Beam in a tail extending beyond the unstable fixed point will be driven beyond the momentum acceptance of the ring and willbe lost. This change in lifetime then becomes a way to selectively explore the outer fringes of the momentum distribution of the stored, cooled beam. We could compare the lifetime while the beam experienced inductive acceleration with that during inductive deceleration. The lifetime was shorter during acceleration, perhaps indicating a tail on the high momentum side of the distribution. Interactions with electrons on molecules of residual gas in the imperfect vacuum should generate a low momentum tail.

When slow accumulation is used to increase the intensity of the cooled beam, a variety of new phenomena appear, some of which are briefly described in the following section.

Instabilities at High Cooled Intensities

The first indication of intensity-dependent changes in beam character occurs in the oscilloscope display of beam time structure seen by a wide bandwidth wall gap monitor. For example, when operating on ninth harmonic, and triggering the scope on one of the nine pulses, the other eight are seen to undergo relative coherent synchrotron motion with respect to the one selected for triggering. This motion has a well-defined threshold (about 40 μA for 45 MeV protons).

As higher intensities are accumulated, a sequence of patterns of relative sychrotron phase is observed, sometimes accompanied by different numbers of particles in different buckets. At the highest intensity so far achieved with a cooled beam with rf on (about 2.2 10^9 particles stored), the pattern was again stable. The same sequence of different oscillation patterns (in reverse order) is seen if filling is stopped and the intensity allowed to decay slowly.

The Schottky signal for these intensities using coasting accumulation (no rf) showed in more dramatic form the signal splitting shown above for $^3He^{++}$. In addition a coherent signal appeared on the upper horizontal betatron sideband with a definite intensity threshold. Lacking an absolute current monitor for the coasting beam, we can be less definite about the current threshold for this instability.

Experiment Preparations

There are now 13 Cooler experiments selected by our program committee and in preparation or awaiting scheduling. These cover accelerator physics (Siberian snake proof-of-principle, collective effects in well-cooled beams), atomic physics (charge-changing cross-sections, dielectronic recombination), and nuclear and particle physics (pion production near threshold, radiative capture, pionic atom formation, tagged polarized neutron beam formation, etc).

Because the internal target operation of a cooling ring is an unfamiliar environment for most of our users, a fair amount of time during our development runs has been given over to a hardy experimental group braving the rigors of conditions during machine commissioning to develop the basic setups that, with variations will serve many future users. [6] There have been for example three kinds of targets in the ring; gas jet, fiber, and slab edge. Fixed and moving collimators have been and used installed to explore their influence on aperture, lifetime and backgrounds at the detector position in one of the long straight sections.

The jet target showed us that the main influence of target material in the path of the cooled beam was a lifetime reduction attributed to emittance growth. The longitudinal momentum spectrum retained its narrow peak up to quite large target thicknesses (eg. 10^{14} N_2 atoms/cm^2). It was also discovered that a background component proportional to target thickness could be induced in the beam and that its removal required careful control of beam position at remote locations in the ring where effective acceptance apertures were located. We now believe that this was due to the use of a ring tune that gave a vertical beam size at the differential pumping apertures larger than the size assumed in the aperture design. The same tune caused a shift in the beam waist position at the kickers and reduced the ring acceptance by about a factor of two.

The collimator studies showed that the cooled beam could be moved within 3 mm of an obstacle near a target waist before the lifetime was reduced. Monitoring changes in detector background rates is a more sensitive beam tail indicator than is a change of lifetime.

Moving the beam across a fiber or a fiber across the beam showed the cooled beam dimension to be on the order of half a millimeter [5].

The slab target with a controlled beam spill provides a conveniently high efficiency of beam use, allowing polarization studies to begin before the stacking process was able to provide higher polarized beam intensities.

It has proven rather difficult to cleanly block stray beam from the cyclotron from entering the Cooler room when the cyclotron beam is being shared by switching back and forth between the Cooler and other users. We now routinely add a second pulsed magnet downstream of the main splitter and have installed a third gate further upstream for greater suppression. Spill monitors on the ring show little rate difference, once the cyclotron beam is completely blocked, between no beam in the ring and 0.1 mA stored and cooled.

The experimenters have learned to build wire chambers with holes through which the stored beam passes, and which have high voltage that can be gated on and off to protect against higher spill rates during inefficient ring filling and losses of beam tails prior to cooling.

Neutrals from H_2^+ in Cooling Electron Beam

The measured lifetime of 0.1 s was the same within 10% whether an electron beam of 0.3 A was present or absent. The neutral rate observed in a detector downstream of the cooling region was increased by 20% to 50% when the electron beam was switched on, relative to a base level indicating dissociation by the 2 nTorr background gas in this 15 m portion of the ring. We interpret this pair of observations as a preliminary indication that with a further reduction of a factor of 5 to 10 in ring pressure, it will be possible to cool and accelerate these ions.

A caveat is that since the lifetime was too short for cooling to be established, it cannot be confirmed that the H_2^+ beam path coincided with the electron beam over the full 2.7 m of the cooling region solenoid, and that the relative velocities were low enough that the maximum possible dissociation rate in this cold electron target was observed.

Conclusion

The IUCF Cooler is in transition to operational status with first experiments underway and an appreciable fraction of its large parameter space explored. We have had glimpses of the good resolution, small emittance, good reproducibility and easy energy variability that motivated the construction of this research tool. Nothing has yet appeared to refute the predictions with which construction was justified. Much challenging work remains however before we reach the outer fringes of its performance envelope.

Acknowledgement

The author is one of a group of more than fifty persons who have worked on the Cooler project since its inception. The intense activity of the commissioning phase has involved a dedicated group of about 20 individuals who have shouldered the burden of making this complex facility an operational reality. They share the credit for the accomplishments reported here, but are not to be held accountable for any errors in the recording of their work by the present author.

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