STATUS REPORT ON THE INITIAL COOLING STUDIES IN THE IUCF COOLER

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Abstract

Proton beams with kinetic energies of 45 and 148.8 MeV have been cooled in the IUCF Cooler with electron beam currents (densities) ranging from 0.2 to 0.75 A ($15 - 100 \times 10^6/cm^3$). After a brief summary of the Cooler commissoning, we describe the electron system, its commissioning and the results of preliminary cooling measurements. Some of the experiments and enhancements planned for the Cooler in the near future are also briefly mentioned.

Introduction

The IUCF Cooler[1] is one of many small electron-cooled storage ring/accelerators under construction for studying nuclear and atomic physics. The initial Cooler commissioning period began at the end of 1987 and ran through May 1988. During this period many important milestones were achieved: Using stripping injection of 0.2 - 0.5 μA, 90 MeV H_2+ beams, up to 200 μA of beam has been stored in the Cooler with uncooled (cooled) lifetimes of about 2 (30) seconds. The beam has been accelerated to 65, 148, and 250 MeV. Single turn kicker injection and cooling of 148 MeV polarized protons was also achieved, where uncooled (cooled) lifetimes of 5 (150) seconds were observed. The cooled-beam lifetime without rf was usually twice as long as those quoted above. In addition, elastic scattering of particles in the cooled beam from an internal N_2 gas jet target has been observed using the apparatus for CE01, the first Cooler experiment which was designed to measure neutral pion production near threshold.

A few shifts within this development period were devoted to studying the cooling process, and to studying the combination of beam cooling with electrons and heating by an internal target. The body of this paper will concentrate on these preliminary measurements.

The Electron Cooling System

The electron cooling system[2] was designed to provide a 2.54 cm diameter electron beam with currents up to 4 A, and energies up to 270 keV.

Magnetic Field Measurements and Corrections

The magnetic measurement system has been previously described.[3] The use of the autocollimation telescope allowed us to make measurements of the transverse fields in the solenoid with an accuracy and repeatablity of <0.05 Gauss in the presence of the 1450 Gauss longitudinal field. Initially the main solenoid had transverse field components of about 5 Gauss (peak-to-peak). After the addition of 2 horizontal and 2 vertical correction coils, the transverse field was reduced by over an order of magnitude, resulting errors on axis of 50 and 80 μrad rms repectively.

A simple particle tracking program was written to simulate the passage of electrons through the large (200 Gauss) measured field errors caused by "missing turns" of current-carrying conductor where the solenoids and toroids join. The results of the tracking program showed that the electrons adiabatically traverse these field errors; in fact, when the field errors were reduced by an order of magnitude, the motion became nonadiabatic due to a decrease in field error wavelength. Thus the errors were left uncorrected. By the same reasoning, there are no dipoles inside the 60° toroids. The adiabatic centripital drift inside the toroids is compensated for by steering the beam in the gun and collector acceleration columns. Work is continuing in modeling the motion of the electrons through the toroids.

System Commissioning

The start-up for this system, which took place on the evening of March 30, was routine. During the first evening of operation the system was operated with 1 Amp of electron beam at energies up to 125 keV (the maximum design energy without the use of SF_6) with collection efficiencies as high as 99.99%.

Although the system recieved a hard bake at 300°C, it had been opened to air for 24 hours prior to operation. The system pressure, which was about 1 μTorr during first operation, dropped to about 2 nTorr after a few days of operation, a pressure consistent with the average ring pressure.

Collection efficiencies, without tuning, are typically greater than 99.9%, although with careful tuning, efficiencies as high as 99.995% have been observed. Data on collection efficiencies is being collected to test with our theories.

The high voltage power supply appeared to be stable to within about 1 V_{pp} during most of operation as measured by the the coasting beam Schottky signal frequency drift. However, during our final run, drifts as large as 2 V were observed. The source of this drift is not yet known. Although the main high voltage power supply is most suspect, very samll changes of the electron beam current, either the proton or electron beam position, the amount of space charge, the internal electrode bias, and even the shape of the high voltage power supply ripple could account for the small cooled-beam energy drift that we observe. The high voltage power supply also has a 60 Hz ripple component of 4 to 10 V, and 360 Hz component of about 2 V amplitude. A ripple-bucking system which feeds the ripple voltage forward to an isolated electrode inside the cooling section is in place and should reduce the effect of this ripple by over an order of magnitude.

Measured Properties of the Cooled Beam

Measurements of cooling were made with 45 and 148 MeV proton beams. The electron guide system magnetic field was 1.16 kG during these measurements. Much of our data on cooling is still preliminary; most of it has not been critically analyzed or reproduced, as is explained with the data presentation.

Longitudinal Drag Rates and Equilibrium Distributions

Equilibrium Energy Spreads: The cooled-beam momentum spread is measured by observing the coasting proton beam Schottky signal frequency spectrum. Both at 45 MeV and 148 MeV we observed cooled-beam energy spreads (FWHM) of about 2 keV, corresponding to *momentum* spreads of 2.2×10^{-5} and 7×10^{-6} respectively.

These energy spreads are equivalent in magnitude to the coherent shift in energy which we observe, which corrosponds to a 1 V change in the electron beam energy. The energy spreads are also about twice the minimum amount which one would expect due to the measured longitudinal drag rate and 60 Hz high voltage power supply ripple alone. Thus we appear to be in the position where increasing the beam current, and thus the longitudinal drag rate, may increase the time-averaged cooled-beam energy spread, though this has not yet been tested.

Longitudinal Drag Rates: The longitudinal drag rate has been measured in two different ways. One method involves exciting the electrode within the cooling section with a 50 to 100 V amplitude sawtooth waveform (much larger in amplitude than the 60 Hz ripple on the high voltage power supply). The maximum frequency of modulation which the proton beam can track is then measured by observing the amplitude of the coherent Schottky signal frequency modulation. These measurements were made using 45 MeV proton beams and electron beam currents of 0.4 and 0.22 A. The corresponding measured drag rates were about 215 keV/s and 130 keV/s, about twice the value we expected[4] according to the nonmagnitized-theory assuming a transverse electron beam temperature of 0.2 eV.

One disturbing inconsistency in these data is that the proton beam energy shift is almost exactly half what is expected when a constant potential is applied to the electrode. The electrode is split down the center longitudinally, so one possible explanation is that the potential is only appearing on one of the two halves. The hardware, externally, appears to be in working order. Another explanation is that there are space charge effects which we do not understand. There is a drift electrode system for controlling the space charge consisting of 11 electrodes, 7 of which are split for different reasons, such as the removal of stray electrons from the system, or for beam position measurements. The electrodes are biased progressively more negative along the beam direction, thus sweeping positive ions to the collector, and electrons to the gun toroid, where the combination of centripital and **E** x **B** drift (from the split electrodes) should remove them. This should permit us to modulate the electrode inside the main solenoid without trapping electrons or ions, providing the potential stays within the bounds of the adjacent electrodes. Erratic changes in the proton beam energy were observed when only the main solenoid drift electrode were biased negative. These energy shifts disappeared when the other electrodes where biased. It is not known whether these other electrodes were operated during the first set of measurements. The pressure inside the main solenoid during the measurements was a few nTorr.

We are not certain that the proton and electron beam angles in the cooling section were properly aligned during any of our measurements. During the first set of measurements the field-straightening correction coils in the main solenoid were not energised.

The longitudinal drag rate can also be deduced by observing the rate at which the time spread of an rf bunched beam is reduced, as shown in Fig. 1. The incoming beam was bunched at h = 9, and the ring rf system was operated at h = 6; the electron beam current was 0.49 A, the rf cavity voltage 2 kV; and the ring transition energy is $4.85 \cdot Mc^2$. From this measurement we get a rough estimate for the rate of change in the amplitude of the synchrotron oscillations of 120 keV/s, a value somewhat lower than the measurments made with unbunched beams when the oscillatory motion is taken

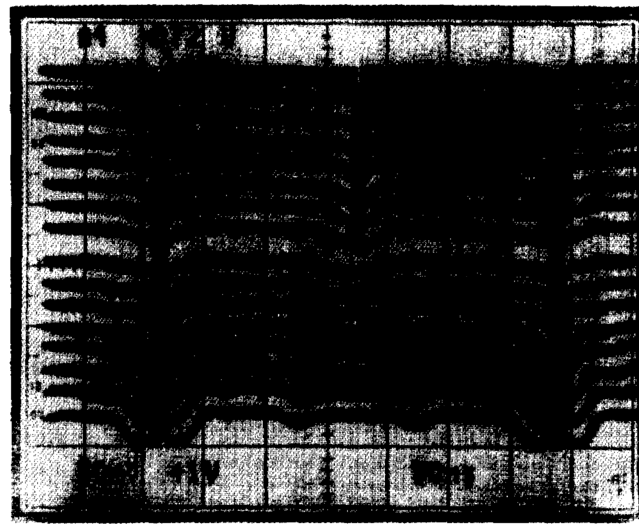

Figure 1. Display of longitudinal cooling; the signals are from a beam position electrode. (0.132 seconds/trace).

into account and the result is normalized to the electron current.

We attempted to observe the effects of intrabeam scattering by recording the Schottky signal frequency spectra for coasting proton beam intensities of 10 and 1 μA; no significant reduction in energy spread was observed, though the energy spread for the lower intensities may have been marginally lower. We also looked at the equilibrium proton beam energy spread as a function of electron current; again no significant change was observed, though the distribution may have been marginally narrower for lower electron currents. We did, however, observe that the beam lifetime increased nearly linearly with beam current.

Transverse Cooling and Equilibrium

Trasnverse beam profiles were generated by sweeping the beam very quickly across a 7 μm diameter carbon fiber and detecting the current from knock-off electrons. The fiber is located in a high dispersion region of the ring, and the sweeping accomplished by accelerating the beam with rf. The design lattice functions at this location are: $\eta_x = 4.15$ m, and $\beta_x = 0.89$ m. However, these lattice functions have not been measured at this location recently, and thus the calibration could be in error. The beam from the cyclotron has a momentum spread of about 0.05%, and an emmittance of about 2π mm·mr. The initial momentum spread is slightly higher due to small mismatches between the cyclotron and Cooler circumferences, and the initial emmittance may be somewhat higher due to injection mismatches and repeated passages (a few times 10^2) through the 15 μg/cm^2 carbon stripping foil. Thus at injection, the beam width at this location has significant contributions due to both its momentum spread and its emmittance. After cooling, however, in the absence of rf, the cooled-beam size is dominated by the transverse emmittance. However, with rf, a 1/2-least-significant-bit change on the electron beam high voltage power supply 16 bit DAC would produce a 2.3 eV electron beam energy change. This would result in an equilibrium beam size equivalent to that which we have measured. Thus, these measurements only give an upper limit on the beam emmittance. Fig. 2 shows the time evolution of a 45 MeV proton beam cooled with a 0.22 A electron beam.

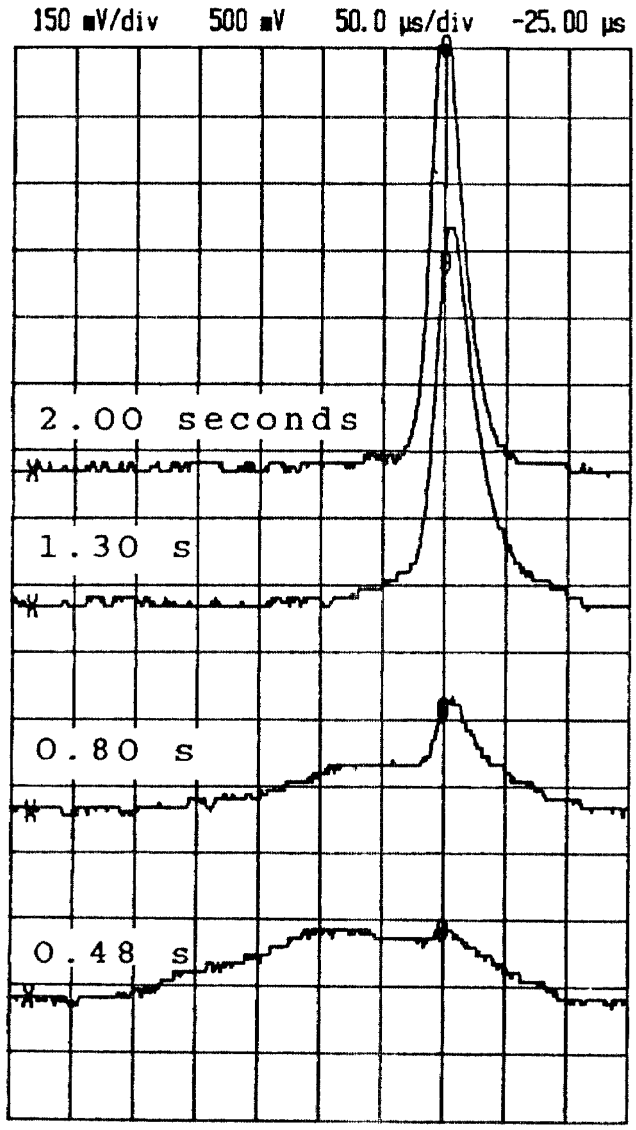

Figure 2. Transverse profiles of 45 MeV proton beam cooled with a 0.2 A electron beam. Profiles taken where β_x = 0.89 m, η_x = 4.15 m. (0.6 mm/div).

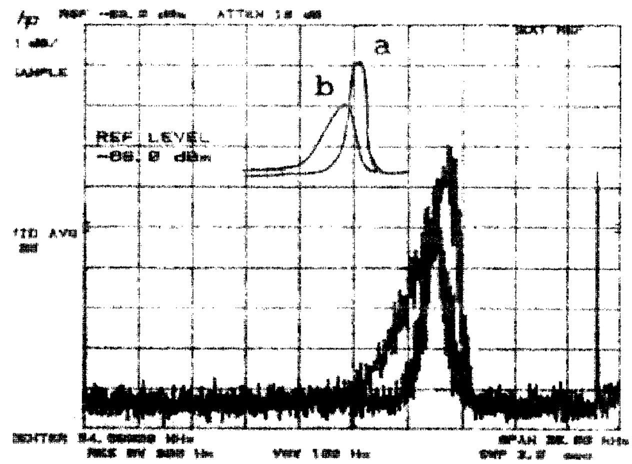

Figure 3. Schottky signals from a 45 MeV proton beam: (a) target off; (b) target on. The harmonic number is 53. RBW = 300 Hz, CF = 54.7 MHz, 2 dB per division, 3 kHz per division.

Electron Cooling and Target Heating

Some measurements of a 48 MeV proton beam interacting with a target of thickness approximately 7 x 10^{13} N_2 atoms/cm^2 and a 0.5 A electron beam were made. We observed, surprisingly, that the beam lifetime was longer for coasting beams than it was for rf bunched beams. For bunched beams, the lifetime was reduced from 22 to about 1.3 seconds. Another set of measurements made with coasting beams and targets of about the same thickness showed that the beam lifetime varied approximately as the target thickness to the minus 3/2 power. For coasting beams, we also observed that the cooled-beam energy spread remains relatively small but grows a low energy tail, as shown in Fig 3. In addition, there may be a slight coherent downward shift in the stored beam energy, though this energy shift is on the order of the energy spread of the unheated beam and the amount of coherent energy shifting which is constantly taking place.

Future Enhancements to the Cooler

The Cooler is now in a position to begin studying some of the intricacies of performing nuclear physics experiments in a storage ring environment. In the upcomming year we will begin the experiment, install the hardware necessary for stacking fully-stripped beams, and the equipment necessary for testing the Siberian Snake idea (CE-05) for polarized beams.

The electron system will be operated at higher energies and currents, and systematic cooling studies will be performed over a large dynamic range in order to clearly observe subtle effects. Machine studies of acceleration and apperture limits will continue.

Acknowledgement

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References

[1] R.E. Pollock, "The Indiana Cooler project," in Proc. of the 11th Int. Conf. on Cyclotrons and their Applications, 1987, pp. 123-127.

[2] Otto C. Dermois, Timothy J.P. Ellison, D.L. Friesel, "The Indiana University Cyclotron Facility electron cooling system," in Proc. of the 11th Int. Conf. on Cyclotrons and their Applications, 1987, pp. 153-156.

[3] O.C. Dermois, "The design of homogenious field solenoids for the IUCF cooler section," in Proc. of the 11th Int. Conf. on Cyclotrons and their Applications, 1987, pp. 288-291.