PROGRESS IN COMMISSIONING THE IUCF COOLER*

T.J. Ellison, W.P. Jones, J.C. Collins, D.L. Friesel, P. Schwandt, and T. Sloan
Indiana University Cyclotron Facility
2401 Milo B. Sampson Lane
Bloomington, IN 47408-0768

Abstract

This paper will describe some of the techniques used and results observed during the commissioning of the IUCF electron cooled storage ring. Measurements of machine properties and their comparison with design values, methods of closed orbit corrections, and the methods used in ramping the beam to higher energies will be discussed. Plans for enhancing the performance of the ring will be described.

I. Comparison of measured and calculated machine parameters

A. Beta Functions and Tunes

1. Measurement technique: RF signals were applied to horizontal or vertical kicker plates and the frequency varied to determine the frequencies at which beam lifetime was strongly reduced. Comparison of those frequencies with the orbit frequency yields the horizontal or vertical fractional tune. Beta functions averaged over the length of the quadrupoles were determined by measuring the tune shift for a given change in the strength of a specific quadrupole.

2. Coupling effects: In principle, one need only measure the betatron tune for two slightly different settings of an individual quadrupole to determine the average beta functions at the quadrupole location. However, in the early commissioning of the cooler, dispersion at the location of the rf system created a situation where the betatron frequency spectra had about five strong synchrotron oscillation sidebands (spaced at $2f_s$, where f_s is the synchrotron oscillation frequency). In addition, skew quadrupole fields from the fringe field of injection elements strongly coupled the horizontal and vertical tunes, so that frequencies which would knock out the beam when applied to a horizontal kicker, would also knock out the beam when applied to a vertical kicker. To exacerbate matters, the vertical and horizontal tunes were almost precisely the same (i.e. $\Delta Q_x - \Delta Q_y \sim f_s$). This created a situation where, after making a small change in a quadrupole field, it was essentially impossible to find the same sideband on the betatron spectra of the same plane in the machine. To deal with this problem, we would "track" a knock-out resonance by changing the quadrupole setting in steps small enough so that the tune would change by an amount which was small compared to the spacing between knock-out resonances.

However, even in this case, matters were still ambiguous, since the knock-out frequencies would not vary linearly with quadrupole strength as the vertical and horizontal sideband frequencies periodically overlapped with the change in quadrupole strength. This is shown graphically in Figure 1. The change in tune with change in quadrupole strength (beta function) had to be determined by extrapolating the curves at the end of their range, away from the working point.

B. Dispersion functions

The dispersion functions were measured by frequency modulating the rf ($\pm$ 0.1% $\Delta f/f$) with a 10 Hz triangle waveform, and measuring the amount of position movement around the ring at each of the 36 beam position monitors (BPMs). The electronics are sensitive enough and have enough bandwidth to make this measurement for beam currents greater than a few hundred nA. An example of such a measurement is shown in Figure 2. This system is especially sensitive for observing small amounts of dispersion where none should exist (e.g. in the vertical plane).

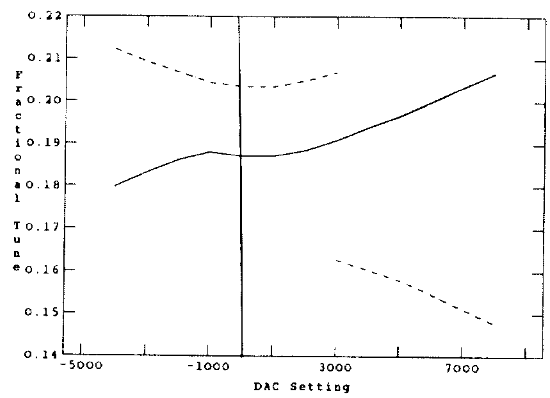

Figure 1. Measured fractional tune vs. quadrupole strength (arbitrary units). The solid line is the "horizontal" and the dash-dot line the "vertical" fractional tune.

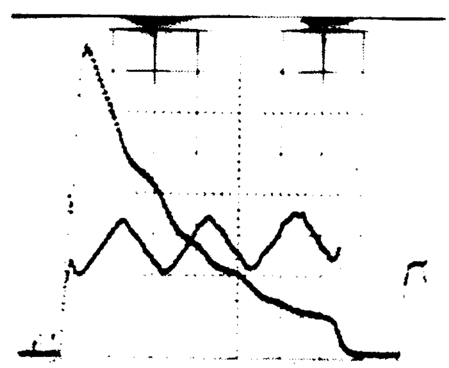

Figure 2. Beam dispersion measurement. The triangular waveform is the beam position, and the exponentially decaying waveform the beam intensity signal, both from the Beam Position system.

C. Comparison of measurements with lattice calculations

The initial measurements of the fractional tune did not give very good agreement with the design calculations carried out with MAD[1]. The difficulties were traced to two sources. The bulk of the magnetic field mapping of the main dipole magnets had been done with isolated magnets. The magnets in the ring are used in pairs and the edge angles of the pairs were found to be shifted a fraction of a degree because of the presence of the second magnet. The second uncertainty was the absolute strength of the quadrupole magnets. An overall renormalization of 0.8% was found to be needed to make the measured tunes agree with those calculated using actual quadrupole currents. The first correction affects primarily the horizontal tune while the second affects both

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vertical and horizontal tunes. After making these adjustments there was reasonable agreement between the measured dispersion and beta functions and the calculated values. Figure 3 shows a comparison of the measured values of the beta functions for one section of the ring. The agreement seen here is typical of the ring as a whole. One consequence of the changes in dipole magnet geometry is that the vertical acceptance of the ring is somewhat reduced from the original value of 25 pi mm-mr. Work is presently in progress to develop new tune conditions to restore the acceptance to its original value.

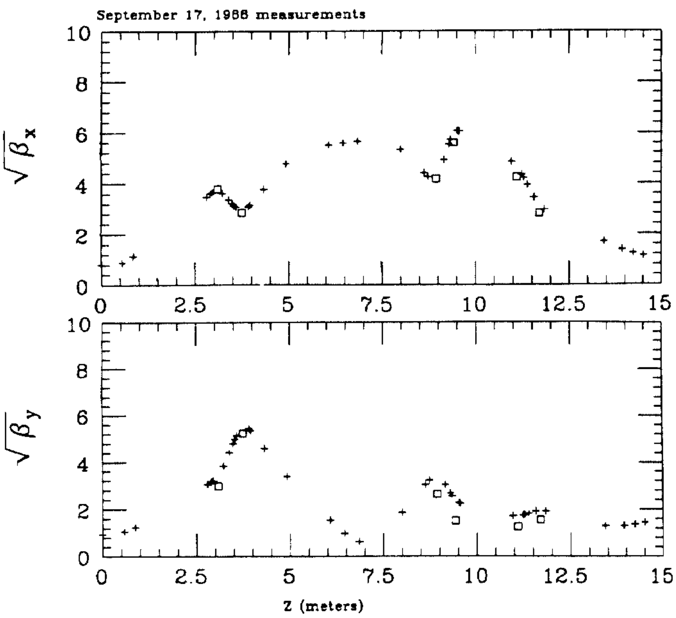

Figure 3. Comparison between measured beta functions (open squares) and calculated values (+ signs) for one sixth of the ring.

II. CLOSED ORBIT CORRECTIONS

A. Injection

1. Optimization of Injection Bumper Magnets: Three "bumper" magnets are used in the cooler injection region to produce the vertical orbit distortion required for stripping injection. To localize this distortion to the injection region while allowing for tuning the magnet triplet to optimize injection, a COMBO pseudo-device was created as a linear combination of these three magnets. Appropriate coefficients were determined by observing beam position signals from pairs of vertical BPMs separated by 90 deg. in phase while varying individual magnets to obtain minimum deviations in beam position between bumper on and bumper off conditions. The COMBO so generated can maintain the bumper on/bumper off orbit changes to less than 1.0 mm through most of its useful range.

2. Injection errors: The BPM system can be used to measure both the closed orbit beam position, as well as the first turn beam position. By taking the difference between these two measurements, the magnitude and phase of the injection error can be isolated. Measurements show that up to 50% of the available aperture is used up by vertical injection errors, and 60 - 80% by horizontal errors.

Orthogonal COMBO'S for adjusting the position and angle of the injected beam with respect to the closed orbit were developed to reduce the amplitude of the injection errors. It was found, however, that the injected beam was lost before either the position or angle of the injected beam could be significantly altered. We thus suspect that there are physical alignment problems that must be addressed.

We have, however, been able to use vertical injection errors to our advantage. One method of injection into the Cooler is to use the three vertical bumper magnets to move the closed orbit up onto a 15 μgm/cm^2 carbon foil for stripping injection of a 45 MeV H_2^+ beam. Per chance, we found a way to inject beam into the ring through the stripping foil while having the closed orbit pass below the stripping foil. After electron cooling has reduced the size of the stored beam to submillimeter dimensions, the bumper magnets can be subsequently turned on to inject another batch of beam without affecting the stored beam intensity or lifetime. Using this technique, we have been able to repeat the injection process at about a 2 Hz rate and accumulate about 100 stacks of beam. Accumulation of beam using this technique is shown below in Figure 4.

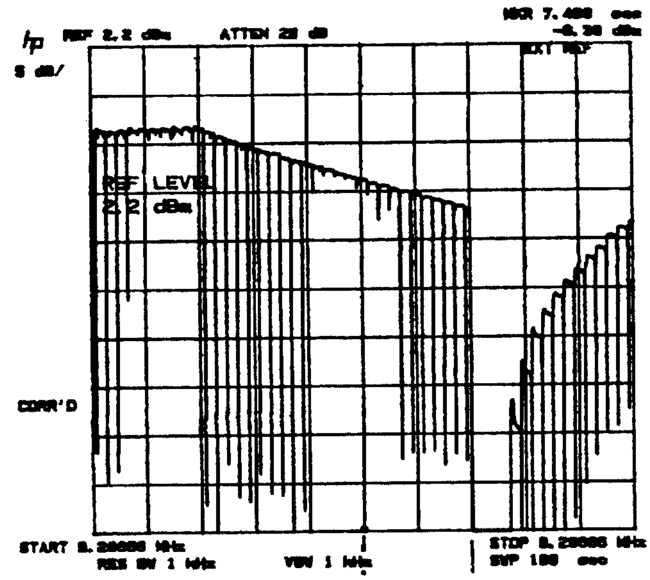

Figure 4. Accumulation of beam at 0.5 Hz using electron cooling. (10 s/div; 5 dB/div). One observes a 20 dB (factor of ten) increase in stored beam after ten injection cycles (last two divisions of the display).

B. Closed Orbit Corrections

A number of COMBO's consisting of three or four steerers tied together have been defined which generate localized corrections to either the position or direction of the beam in the six straight sections and six corners of the ring. A program has been written which will uses the MAD output for a given tune to generate the strength coefficients for the specific steerers in a COMBO. For a given tune, these coefficients can be archived for use in a later run.

III. RAMPING

A. Ramp Generation

The IUCF Cooler Facility is designed to accelerate ions to B-rho values of up to 3.6 Tm. This process involves ramping some 90 magnets (100 when hexapoles are included) along a precise B-rho vs. time curve having a typical slope of 0.5 Tm/sec. The hardware to accomplish this has been described elsewhere[2]. The ramp data loaded into this hardware consist of pairs of 16-bit slope and endpoint values, each such pair being referred to as a vector. While the hardware can accept up to eight separate sets of 256 vectors, we find that ramps of 30 to 50 vectors give satisfactory results. To date no attempt has been made to determine a minimum number of vectors in an acceptable ramp.

The basic ramp calculation determines a table of B-rho values, changing linearly with time, between the user-specified initial and final energies. Using that table and device starting values read either from the existing machine state or an archive file, tables of current vs. time, I(t), and DAC vs. time, DAC(t), are then calculated. However, essentially every class of cooler devices must be treated differently. The dipole main power supply has a very large filter capacitor across its output, requiring significant modifications to the DAC(t) table to achieve approximately linear load I(t). Steering magnets are unipolar or bipolar and some have non-linear B(I) curves. All hexapoles exhibit non-linear B(I) curves, as do all quadrupoles. Finally, quadrupoles have multiple coils powered by a matrix of supplies, so I(t) tables for groups of quads must be algebraically decomposed into DAC(t) tables for corresponding groups of supplies. Including data retrieval from a disk-based database, a typical ramp calculation requires about 10 sec. on an LSI-11/73 with floating point hardware.

Once calculated, an editing task allows ramps to be modified at the vector level by substituting values for slope or endpoint or modifying the endpoint by a given percentage. Sets of such corrections may be archived and applied to newly calculated ramps. The editing task allows corrections to be applied to COMBO's, changing the ramps for each real device component using the coefficients discussed above. At present, successful ramps are achieved by applying corrections of a few percent to the ramps for the dipole and a few steerers. Now that accelerated beams of long lifetimes have been achieved, a method will be implemented for altering ramps to end at an optimized machine state determined by normal manual tuning operations at the high energy.

Very early we found that, due to very large losses during acceleration, it was necessary to have a logarithmic display of the beam current during acceleration. A logarithmic current detector was added to the BPM system. This detector tracks the frequency of the rf ramp closely enough to be measured with a 50 Hz Intermediate Frequency modulation bandwidth superheterodyne detector, allowing measurement of beam currents down to as low as about 10 nA. The BPM system simultaneously gives a display of the beam position in a region of high dispersion, thus directly showing us the mismatch between the rf frequency (driven by a Direct Digital Synthesizer) and the bending magnet field. The mismatch of the quadrupole strength can only be determined after a laborious measurement of the tunes during the ramp using the rf knockout technique. An example of this measurement is shown in Figure 5.

B. Beam Loss

We have been able to control the beam closed orbit and tunes during acceleration, but still experience excessive losses, only accelerating a few percent of the beam from 45 to 287 MeV (energy threshold for pion production). We now suspect that the rf system is responsible for most of these losses: acceleration efficiency increases as the bucket area is reduced; in addition, a very tightly bunched electron cooled beam expands to fill almost the entire bucket after only a fraction of the acceleration cycle has been completed. We think that noise from the phase-locked loop which is filtering the direct digital synthesizer is causing this beam heating.

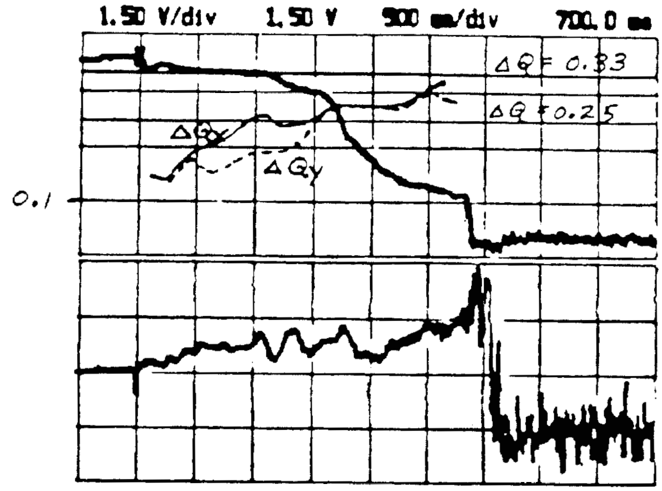

Figure 5. Beam current (upper, 15 dB/div, 20 μA FS) and position (5 mm/div, 0 at ctr) during acceleration from 45 to 287 MeV. The beam is lost at about 287 MeV. The sketched-in lines show the transverse tunes (0.1/div, 0 at bottom).

IV. HIGH INTENSITY OPERATION

Using the beam stacking technique mentioned above in section II.B.2, we have been able to store and cool 45 MeV proton beams with intensities up to 500 μA and momentum spreads of a few 10^{-5}. At these intensities and momentum spreads, many interesting beam instabilities and collective beam effects have been observed, some of which are described in other papers in these proceedings[3].

At a few hundred μA, coherent dipole synchrotron oscillations are excited with every n^{th} bunch in phase, where n depends upon the beam intensity and rf harmonic number. We plan to attack this problem using a wideband damper system, feeding forward the beam position signal from a pickup in a region of high dispersion to a low voltage wideband accelerating cavity located in a region of no dispersion.

In addition to these bunched beam instabilities, many collective effects have been observed with high intensity, electron cooled coasting beams. These are discussed in another paper at these proceedings[4].

ACKNOWLEDGEMENTS

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1. F. Iselin, The MAD Program, CERN-LEP-TH/85-15.

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