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.

A.7. 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.

1. A.D. Krisch, *et. al.*, IUCF Scientific and Technical Report, 1988.
2. R.E. Pollock, Proc. Workshop on Crystalline Beams, Wertheim (Main) October 1988 (I. Hofmann, ed.).

MEASUREMENT AND OPTIMIZATION OF COOLER RING PARAMETERS

J. Collins, D. DuPlantis, T. Ellison, D.L. Friesel, W.P. Jones A. Pei,
R.E. Pollock, T. Rinckel, P. Schwandt, and T.S. Sloan

Beta Functions and Tunes

RF signals were applied to horizontal or vertical kicker plates and the frequency varied to determine the frequencies at which the 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.

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 resulted in several strong synchrotron oscillation sidebands. 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. Since the vertical and horizontal tunes were almost precisely the same it was essentially impossible to find the same sideband on the betatron spectra of the same plane in the machine after varying the quadrupole strength. 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 Fig. 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, where the horizontal and vertical betatron frequency spectra no longer overlapped.

Dispersion functions

The dispersion functions were measured by frequency modulating the RF (± 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) capable of measuring beam currents greater than a few hundred nA. An example of such a measurement is shown in Fig. 2. This system is especially sensitive for observing small amounts of dispersion where none should exist (e.g. in the vertical plane).

Comparison of measurements with lattice calculations

The initial measurements of the fractional tune did not agree well with the design calculations carried out with the synchrotron orbit dynamics code MAD.[1] The difficulties were traced to two sources. The bulk of the main dipole magnets magnetic field mapping had been done with isolated magnets. The magnets in the ring are used in pairs and the interior edge angles of 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 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 vertical and

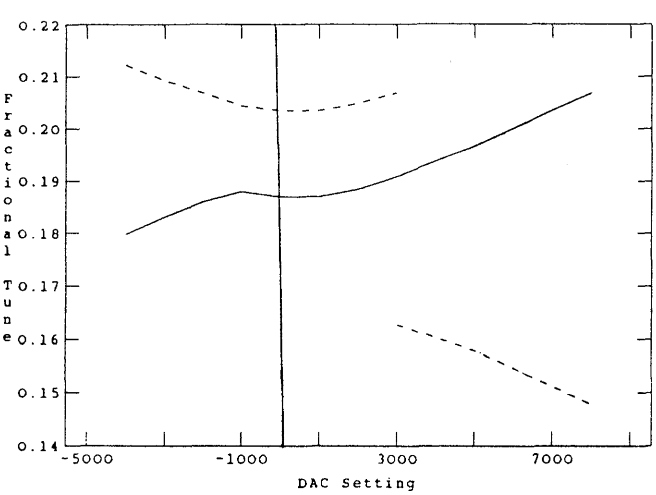

Figure 1. Measured fractional tune vs. quadrupole strength (arbitrary units). The solid line is the "horizontal" and dash-dot line the "vertical" fractional tune.

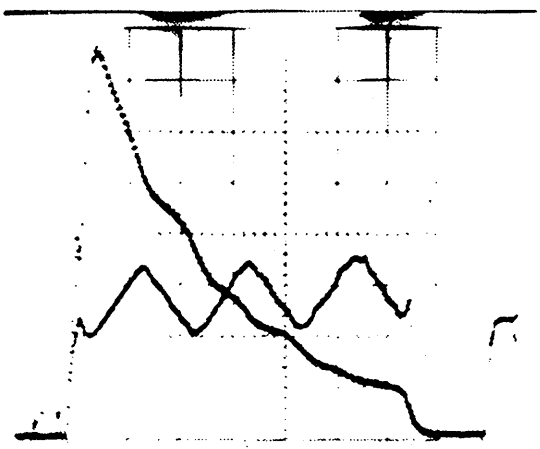

Figure 2. Beam dispersion measurement. The triangular waveform is the beam position, and the exponentially decaying waveform the beam intensity signal, both from the Beam Position system.

horizontal tunes. After making these adjustments there was reasonable agreement between the measured dispersion and beta functions and their calculated values. Fig. 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 π mm-mr. Work is presently in progress to develop new tune conditions to restore the acceptance to its original value.

Initially, we also observed up to 1 m of dispersion in the vertical plane. A pair of skew hexapoles were added to compensate for the fringe field of an injection element which reduced the dispersion to less than 0.2 m in this plane, while also significantly reducing the amount of coupling between the horizontal and vertical planes.

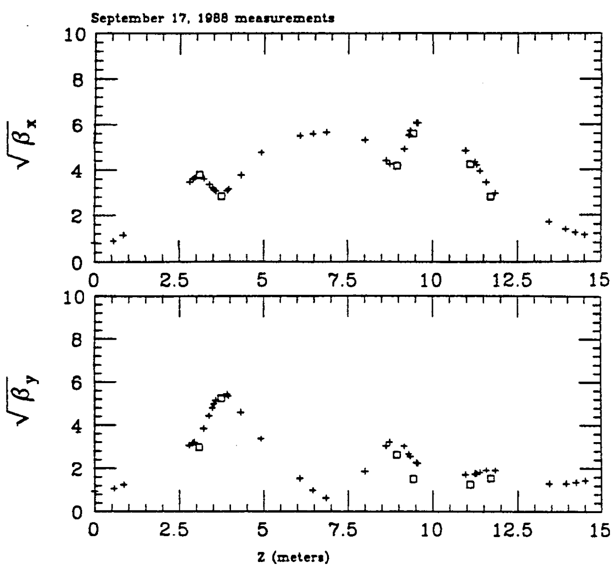

Figure 3. Comparison between measured beta functions (open squares) and calculated values (+ signs) for one sixth of the ring.

Closed Orbit Errors

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° in betatron 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 outside the region of the localized bump through most of its useful range.

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 determined. Measurements showed that up to 50% of the available aperture is used up by vertical injection errors, and 60 – 80% by horizontal errors in the early stages of ring operation.

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 suspect that slight misalignments of critical injection devices may in part be responsible.

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 thin 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 1 Hz rate and accumulate about 100 stacks of beam. Accumulation of beam using this technique is shown below in Fig. 4.

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 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.

We are commissioning a computer program, PLUS,[2] which we received from Stanford to analyze and correct the closed orbit. As a first step, to verify that the program was correctly analyzing steering errors, we compared the predicted and measured closed orbit patterns for every individual steerer in the ring. This set of studies pointed out both strength and polarity errors in our steerer data base, and helped us correct our COMBOS's for local closed orbit adjustment.

Although the program has demonstrated the ability to decrease the closed orbit po-

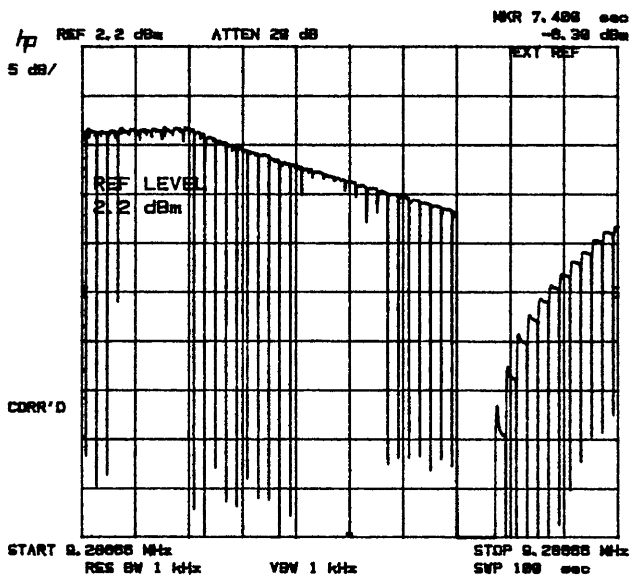

Figure 4. Accumulation of beam at 0.5 Hz using electron cooling. (10 s/div; 5 dB/div). One observes a 20 dB (factor of ten) increase in stored beam after ten injection cycles (last two divisions of the display).

sition errors, there is a severe problem: if we feed the program measured data resulting from a single mis-set dipole, the solution will not only adjust the mis-set steerer, it will correct by changing other steerers or may even set the mis-set steerer more strongly than other steerers in the ring. It will, however, choose to correct the mis-set steerer if it is constrained to only modify a single dipole. This is due to measurement "noise" and steerer "semi-redundancy" resulting from the program lattice model not exactly matching the real Cooler lattice, and because many of the steerers are separated by nearly integral multiples of half betatron wavelengths. We now need to develop a sensible method for constraining the program to develop solutions which minimize both the closed orbit errors and the amount of steering power used in the corrections.

Acceleration

In initial acceleration studies we had quite poor acceleration efficiencies. Problems were identified with the RF system (longitudinal beam heating), ramp calculations (tune shifts and closed orbit errors during the ramp), with our ramp initiation procedure (initial beam loss).

In November 1988 we found that incorrect coefficients for compensating magnet saturation were put into the ramp calculation programs causing the quadrupoles to ramp to values about 2% high in a 45 to 148 MeV ramp. It was still found to be necessary to make a 0.5% correction in either the RF or main dipole fields during acceleration, and experience showed that applying the total correction to the dipole field minimized the tune shift, although we still observe a small tune increase in both planes during acceleration.

In December 1988 we successfully accelerated protons from 45 to 287 MeV, the pion production threshold energy with an efficiency of about 0.3%, or about 3% when compared with the beam lifetime at the injection energy. During acceleration we observed sudden beam losses, and that the beam heated up longitudinally quite rapidly, such that a small bunch would grow and fill the RF bucket soon after acceleration began. These longitudinal heating and intermittent beam loss problems were recently solved by lowering the bandwidth of the phase-locked loop which filters the direct digital frequency synthesizer (DDS). This lower bandwidth smooths the 512 Hz (corresponding to approximately 1% of the machine momentum acceptance) frequency step-changes from the DDS at the expense of letting more random phase noise from the VCO through. A wideband high dynamic range beam phase detector is now under construction to allow us to carefully check that the RF system is not inducing synchrotron oscillations during the ramp. If any significant amount of coherent synchrotron oscillations remain, a feedback loop will be used to damp them.

We are also in the process of improving the main dipole power supply. Presently the feedback transductor is located in a position where it measures the sum of the current through both the load and the filter capacitor in parallel with the load. The transductor is being moved so that it measures the true load current, and more flexible software is being developed to make ramp programing easier. We are also looking at the measured frequency responses of all the quadrupole power supplies (36), which vary from about 200 to 1000 Hz to see if this is causing a significant tracking problem during the ramps.

During the upcoming year we expect to routinely accelerate from 45 to 287 MeV with respectable efficiencies.

High Intensity Operation

With the high currents (several hundred microamps) obtained with stripping injection and cooled-stacking, we observe coherent dipole synchrotron oscillations, with every nth bunch in phase (n depending upon the RF harmonic number and beam intensity) excited in the low momentum spread electron-cooled beams. We also observe what appears to be a fast transverse instability which causes a beam loss above a certain threshold. In the future, we will build fast dampers, which will act on each bunch individually, to damp the longitudinal instabilities.

1. F. Iselin, The MAD Program, CERN-LEP-TH/85-15.
2. M. Lee, S. Clearwater, E. Gheil, and V. Paxson, in *Proc. of the 1987 IEEE Particle Accelerator Conf.*, edited by Eril R. Lindstron and Louiss S. Taylor, IEEE Cat. No. 87 CH 2387-9, (Washington, DC, 1987), p. 611.

ELECTRON COOLING SYSTEM DEVELOPMENT

T. Ellison, R. Brown, and D. Friesel

Summary

The electron cooling system has now been in operation for about 1 year. During this period the system has been tested over much of its design range, operating with electron beam currents up to 2 A and energies up to 250 keV (the energy required for cooling 459 MeV protons). The system has been used for trouble-free cooling of 44 MeV $^3He^{++}$, as well as proton beams ranging in energy from 45 to 287 MeV (the world's highest energy