BEAM DIAGNOSIS FOR UNMEASURABLY COLD BEAMS
-- OR -- "HOW COLD IS IT, AND DOES THE OPERATOR KNOW OR CARE?"

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ABSTRACT

In the first part of this paper, the most unique property of a proton beam in an electron-cooled storage ring is discussed: namely, its extremely small relative momentum spread ($\Delta p/p$, FWHM) and emittance (ϵ, non-normalized, rms). In most cases, due to the very low values of these parameters, their measurement is extremely difficult to perform and interpret; these small values also lead to very low space charge current limitations and threshold currents for instabilities. On the other hand, these same beam properties make the ring an ideal laboratory for studying nonlinear beam dynamics and beam instabilities. A model is conjectured which predicts a suppression of synchrotron oscillations within the bunch leading to a much smaller momentum spread than one would expect when interpreting measurements using the standard independent particle model for the beam.

In the last part of this paper the practical application of beam diagnostics is discussed, and our ambitious plans to make a self-tuning accelerator are outlined.

I. EQUILIBRIUM BEAM PROPERTIES OF AN ELECTRON COOLED PROTON BEAM

I.A. Equilibrium momentum spread

In the absence of intrabeam scattering and space charge effects, the rest frame longitudinal proton beam energy spread is expected to be[1] on the order of $k(T_{e\perp} T_{e\parallel})^{1/2}$, where k is the Boltzmann constant; $T_{e\perp}$ the electron beam transverse temperature, $\approx$ 1300 K or 0.12 eV/k (due to the cathode temperature); and $T_{e\parallel}$ is the longitudinal electron beam temperature, $\approx 2 \times 10^{-04}$ eV/k (determined by longitudinal-longitudinal and longitudinal-transverse electron beam intrabeam scattering)[2]. The lab frame $\Delta p/p$ (FWHM) is $\approx 2.35 \cdot [k(T_{e\perp} T_{e\parallel})^{1/2}/M\beta^2 c^2]^{1/2}$ $\approx 2 \times 10^{-05}$ ($\beta = 0.3$, see Eq.(5)). Magnetized cooling effects are theorized[1] to possibly lead to ever smaller proton beam longitudinal temperatures, on the order of $T_{e\parallel}$. However, for currents above a few μA, proton beam intrabeam scattering is expected to determine the equilibrium momentum spread; indeed, systematic measurements of the coasting beam momentum spread as a function of current appear to show the expected $I_p^{2/5}$ scaling[3].

The coasting beam momentum spread can be measured using Schottky signals, though for currents above a few tens of μA, where the beam has exceeded the Keil-Schnell stability limit, the interpretation is nontrivial[4,5]. Even for lower currents, due to the time involved in the measurement process, one can only measure the time-averaged momentum spread rather than the instantaneous momentum spread. The lowest measured momentum spreads[3] are typically a few $\times 10^{-05}$, with the exception of measurements at Novosibirsk which were as low as a few $\times 10^{-06}$, and which interpreted using a different model.

Measurement of the bunched beam momentum spread, on the other hand, at first glance seems quite straightforward: since there is a simple relation between the momentum and phase spreads of a bunch in an rf bucket, it seems that one need only to measure the beam time spread using a high bandwidth longitudinal pickup. Using this technique at face value, we typically measure bunched beam relative momentum spreads of about 1×10^{-04}; however, as discussed below in the section concerning space charge limits, these measurements indicate that the rest frame electrostatic potential energy across the bunch is much greater than the rest frame kinetic energy spread for beam currents in excess of a few μA; consequently this simple-minded interpretation is probably not correct.

I.B. Equilibrium emittance

The expected proton beam transverse temperature is $\frac{1}{2}kT_e$ when the proton beam is in equilibrium between cooling and diffusion from the electron beam[6,7]. For typical beta functions of 5 m, the equilibrium emittance would be ≈ 0.005 $\pi\mu$m. Emittances about a factor of 4 times smaller are expected in the magnetized cooling regime[8]. Two attempts[9,10] to measure the emittance at IUCF have resulted in measurements of our detector resolution (≤ 0.05 and ≤ 0.02 $\pi\mu$m). We are presently building a single pass flying wire scanner to measure the profiles of a 2 A, 2 MeV electron beam[11]. This scanner will first be installed in the cooling ring for tests and may be able to resolve the beam emittance.

*This work is supported in part by a grant from the National Science Foundation (Grant No. NSF PHY 90-15957).

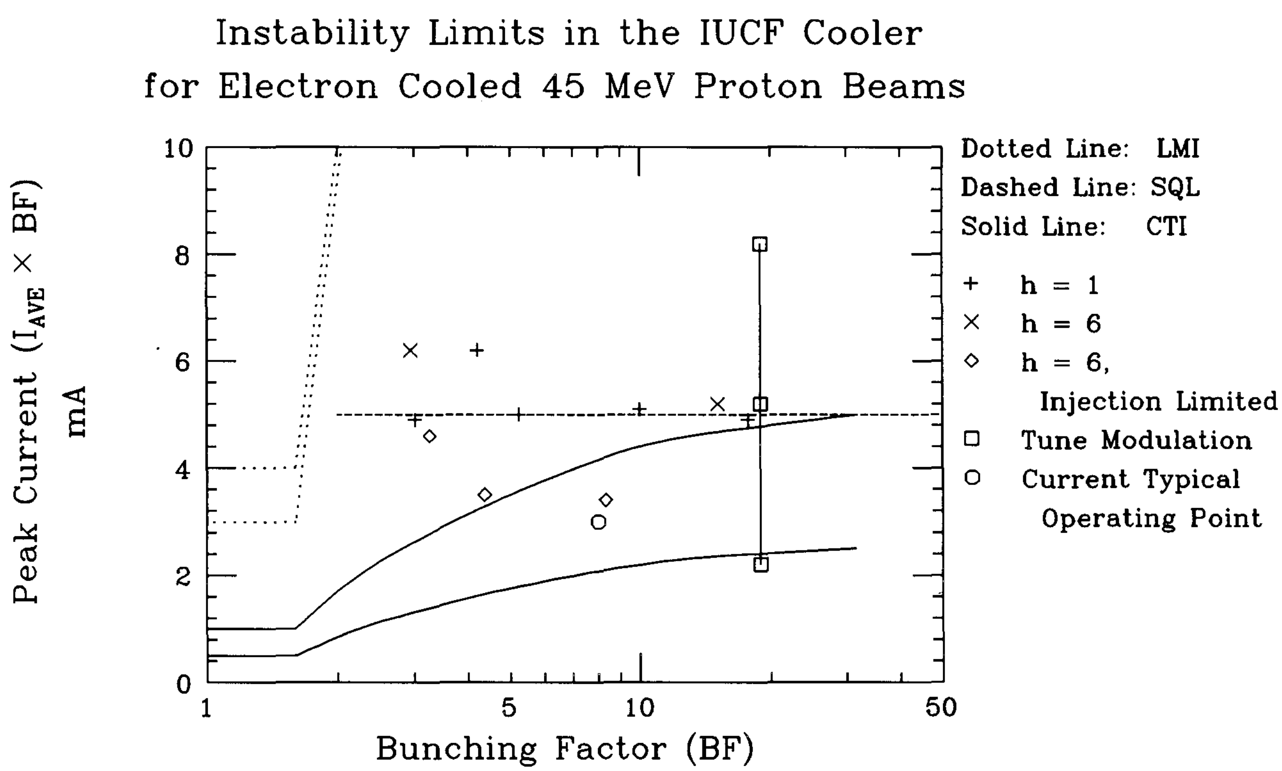

Figure 1. Threshold currents for various instabilities for electron cooled beams in the IUCF Cooler. These curves are based upon measurements and extrapolated according to theory.

The interpretation of these profiles may not, however, be so straightforward: as discussed below in the section concerning space charge limitations, taken at face value these profiles indicate that the particle rms electrostatic potential energy spread is a significant fraction of the rms transverse kinetic energy.

I.C. Intensity limits due to the very cold beams

These cold beams occupy ≈ 2% of the accelerator momentum aperture, and ≈ 0.1% of the transverse acceptance in each plane. This very high phase space density leads to severe limits on the beam intensity: the longitudinal instability threshold current scales as $(\Delta p/p)^2$; the transverse instability threshold current scales as $(\Delta p/p)$; and the space charge current limit scales as ϵ.

In Figure 1 the peak threshold currents (the DC beam current times the bunching factor, B_F (i.e. $B_F = I_{peak}/I_{average}$)) for various current limitations are plotted as a function of B_F for electron cooled 45 MeV protons in the IUCF cooler[12]. The intensity limitations are a function of B_F since as B_F increases from 1 to about 50, the beam momentum spread typically increases roughly a factor 5. The dotted line shows the threshold peak currents for longitudinal microwave instabilities (LMI); the solid curves show the range of threshold peak currents for coherent transverse instabilities (CTI), and the dashed line shows the peak current limitation due to what are presumably space charge effects (SQL).

The transverse instability limit has been removed with a damping system, so apparently a single limitation remains for $B_F > 2$: that due to space charge. This appears to be a "soft" limit: beam is lost at the same rate at which it is added to the ring; no "catastrophic" beam losses, such as occur with transverse instabilities, are observed. Similar "soft" limits seen in electron-positron colliders are tentatively attributed to the beam-beam tune shift[13].

The IUCF system of cyclotrons, with its relatively poor transmission efficiencies, cannot inject enough *uncooled* beam into the ring to reach the *cooled* beam intensity limits. Cooling is then used to accumulate beam until these limits are reached. These limits, as mentioned above, appear to be one or two orders of magnitude lower than the limits would otherwise be for uncooled beam.

Consequently, the technique (electron cooling accumulation) which allows beam accumulation, also precipitates the limitations which prevent the further beam accumulation. We are presently experimenting with methods of transverse beam "heating" to increase the space charge limits. This is a bit more difficult than it sounds since the effects which heat the beam also limit our ability to accumulate beam.

II. THE BEAM SPACE CHARGE

II.A. An interesting variety of ways in which to express the beam space charge tune shift

II.A.1. The space charge tune shift model

It is well known that the large space charge defocussing forces of high intensity, low energy beams significantly affect beam optics. Ion source and electron beam designers routinely calculate the required lens strengths and optics as a function of beam current. Synchrotron people, who generally work with high energy beams having much smaller space charge effects (which scale as $I/(\beta\gamma)^3$ for a constant ϵ, where I is the beam current), refer to these "small" effects as the space charge tune shift, i.e., the small decrease in the transverse oscillation frequency of a particle in the machine. The betatron tune value, Q, (the number of transverse oscillations per revolution in the machine) typically scales as $\approx \gamma^{1/2}$, with low energy machines ($\gamma \approx 1$) exceeding this scaling ratio by about a factor of $\approx 2-5$ (the machine tune stays fixed though the beam energy changes). One considers a space charge tune shift, ΔQ_{SC}, of 0.3 to be very large, and the limit at which a machine should be designed to operate.

Although the mechanism of emittance blow up due to high space charge tune shifts is better known empirically than theoretically, the common intuitive model is that when the tune shift is large, particles will be shifted down onto strong (integer or half-integer Q) resonance lines, or that the nonlinear defocussing fields can drive a variety of higher order nonlinear resonances.

The space charge tune shift for a beam with a Gaussian transverse distribution may be expressed as[14]:

$$\Delta Q_{SC} = \frac{-B_F I R r_p}{2 ec\beta^3\gamma^3\epsilon} \qquad (1)$$

where R is the effective machine radius, r_p the classical proton radius, e the proton charge, c the speed of light, and β and γ are the usual relativistic parameters.

II.A.2. Ratio of the rest frame potential to transverse kinetic energy of a particle in the beam

Another way to view the effect of space charge is to compare the ratio of the rest frame potential energy difference, PE^*, between a particle on axis and at the beam rms radius due to the beam space charge to the rest frame kinetic energy amplitude, KE^*, of a particle with action ϵ. This ratio can be expressed in terms of ΔQ_{SC}, again for a Gaussian distribution, (to within 10%) as:

$$\frac{PE^*}{KE^*} = 2\frac{\Delta Q_{SC}}{Q} \qquad (2)$$

In the IUCF Cooler where the transverse tunes are about 3.7 and 4.7, the ratio of the electrostatic potential energy to transverse kinetic energy is about 0.15 for $\Delta Q_{SC} = 0.3$ using the "average" value of the beta function (R/Q); however, locally in regions where the beta functions are more than an order of magnitude higher than "average", this ratio exceeds unity.

I.A.3. Ratio of the beam plasma frequency to the betatron oscillation frequency

It is also interesting to compare the beam plasma frequency, f_p, (i.e., the frequency at which the beam envelope will oscillate if disturbed) with the beam betatron frequency, $f_\beta = Qf_0$, where f_0 is the beam revolution frequency. Expressing this ratio in terms of the ΔQ_{SC}, on axis for a Gaussian distribution we have:

$$\frac{f_p}{f_\beta} \approx 2\sqrt{\frac{\Delta Q_{SC}}{Q}} \qquad (3)$$

This ratio is typically ½ in most machines operating with large space charge tune shifts. In weak focussing machines with low Q-values (i.e. $Q = 1.2$) this ratio can equal unity for a space charge tune shift of 0.3. (When this ratio is unity, $<PE^*>/<KE^*> = ½$). I would not be surprised to find an instability associated with this condition.

II.B. Longitudinal space charge effects

Since the typical energy spread of a bunched 45 MeV proton beam is on the order of 10 keV, and the total space charge depression across the beam on the order of 0.5 eV, one might naively expect that the space charge has a negligible effect upon the longitudinal beam dynamics. This, however, is not the case. The rest frame electrostatic potential difference between the tails and center of a bunch, PE^*_{TOTAL}, is given approximately by:

$$PE^*_{TOTAL} \approx \frac{2B_F I r_p}{ec}\frac{Mc^2}{\beta\gamma}\left(\left[\frac{1}{2} + \ln\frac{r_v}{r_b}\right] \approx 5\right) \qquad (4)$$

where M is the proton mass, r_v the vacuum chamber radius, and r_b the beam radius. Eq. (4) is correct to within 1% for a Gaussian transverse distribution with $r_v \gg r_b$ if the ½ is neglected and σ is used for r_b.

This potential energy difference is the same for nonrelativistic beams whether measured in the moving or rest frames. The beam kinetic energy spread, however, is *much* less in the moving frame than in the lab frame. In the moving frame, the beam kinetic energy spread, ΔE^*, in terms of the lab frame energy spread, ΔE, is given by:

$$\Delta E^* = \frac{\Delta E^2}{4W}, \quad \text{(nonrelativistic)}$$
$$= \frac{1}{2} Mc^2\beta^2 \left(\frac{\Delta p}{p}\right)^2, \quad \text{(relativistic)} \qquad (5)$$

where W is the beam kinetic energy.

In the IUCF cooler, for a modest beam current of 100 μA, $B_F = 15$, $W = 45$ MeV, and ΔE equal to 10 keV, the ratio $PE^*_{TOTAL}/\Delta E^* > 5$. Consequently we cannot, as mentioned above, trivially discern the beam momentum spread from its phase spread. This effect is elaborated upon in the following two sections.

III. Nonlinear Beam Dynamics Studies

These beam properties which are a bane for the accelerator physicist trying to maximize the stored beam intensity, are a boon for the accelerator physicist wishing to study nonlinear beam dynamics. The very low beam momentum spread and emittance allow the mapping of nonlinear phase space with high resolution and provide relatively large decoherence times for both longitudinal and transverse induced coherent oscillations. In other words, the beam bunch behaves very much like a single macro particle. An example of a transverse phase space map[15], i.e., a turn by turn mapping of the beam bunch in phase space, is shown in Figure 2.

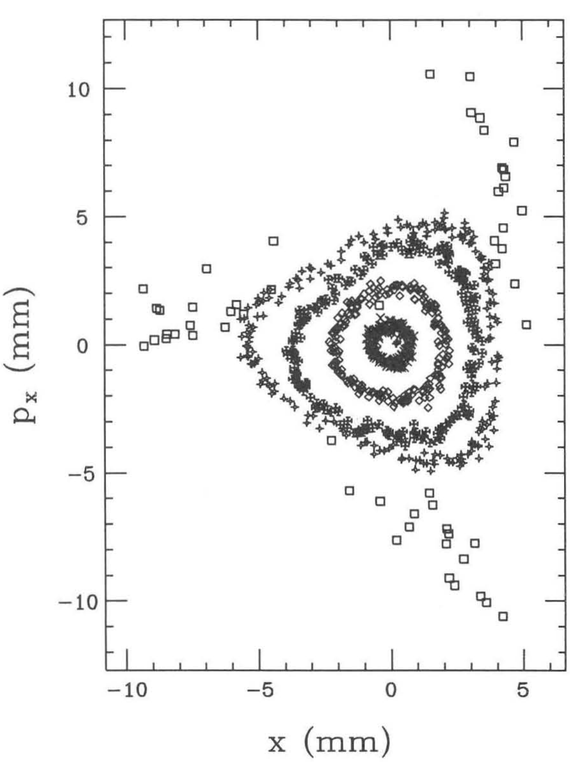

Figure 2. Poincaré map for motion near the 3rd integer resonance.

In the most simple-minded model one expects transverse oscillations to principally decohere due to the machine chromaticity, $\xi = (\Delta Q/Q)/(\Delta p/p)$; though there is also decoherence from the effect of octupolar fields which cause the tune to vary linearly (quadratically) with the betatron amplitude (action). In our machine, the first effect should dominate. The natural chromaticity for a machine is typically about - 1.3. Consequently, with a momentum spread of about 1×10^{-04} and $Q \approx 4.75$, we expect significant decoherence in less than 10^3 turns. If the synchrotron period (longitudinal oscillation period) is much shorter than this, and if we only consider linear chromaticity, the coherence time should be extremely long. This is not the case in our machine, yet it is not unusual to observe coherence for 10^4 or more turns!

Similar effects have been observed in longitudinal phase space. Artificially-excited longitudinal oscillations have been observed to stay coherent for 1 or 2 orders of magnitude longer than a single-independent particle model would predict given the beam time spread and consequently synchrotron tune spread.

Consequently, the electron-cooled beam bunches behave even more ideally than we ever expected; this is good news, but the question remains, why does the electron-cooled beam behave orders of magnitude more like a single particle than an ensemble? Here I conjecture the unexpectedly-long decoherence times are due to the longitudinal space charge effects mentioned earlier. Due to the high ratio of the rest frame particle electrostatic potential energy to kinetic energy, particles are not freely rotating in the bucket (i.e., the expected phase focussing); instead, the conservative electrostatic forces which are trying to make the beam expand, are in equilibrium with the conservative force from the rf cavity. This behavior in longitudinal phase space can also explain the unexpectedly large transverse decoherence times as well, since the beam momentum spread may be significantly lower than what we simplistically infer from a measurement of the beam time spread. In the following section I model this conjecture quantitatively.

IV. THEORY OF A STABLE BUNCH WITH NO DECOHERENCE

IV.A. Model development

Let us conjecture that the equilibrium proton beam momentum spread is essentially zero; let us further conjecture that the bunch will coherently oscillate at the nominal synchrotron oscillation frequency, but particles within the bunch will not due to the space charge forces: in other words, the space charge forces trying to expand the bunch are exactly balanced by the forces exerted upon the beam by the rf cavity which is trying to compress the beam. Starting with this conjecture we can solve for the equilibrium beam distribution.

Since the typical bunch length, a few meters, is so much greater than the vacuum chamber radius, $r_v \approx 0.04$ m, we can easily find the longitudinal force exerted on the particle by the beam electromagnetic forces: it is merely the derivative of the potential energy of a particle on axis with respect to the longitudinal coordinate, s. (Note: as in Eq. (4), the logarithmic term is an order of magnitude larger than the constant term, ½, for a well cooled beam so the spread in potential energy across the beam transverse dimension is neglected; here, I use $\ln(r_v/r_b) = 5$.) In the laboratory frame we can express this force, $F_\parallel$, as:

$$F_\parallel(s) = \frac{-10Mc^2 r_p}{ec\beta\gamma^2}\frac{dI(s)}{ds} \tag{6}$$

where $I(s)$ is $\beta c \rho_l(s)$, with $\rho_l(s)$ the beam linear charge density. Noting that $F^*_\parallel = \gamma F_\parallel$, and $f^*_0 = \gamma f_0$, the change in rest frame momentum per turn in the machine, Δp^*_{SC}, for particles as a function of s due to the beam space charge is:

$$\Delta p^*_{SC} = \frac{4\pi\ln(r_v/r_b)}{\beta^2\gamma^2}\frac{Rr_pM}{e}\frac{dI(s)}{ds} \tag{7}$$

The particle rest frame momentum change per turn, Δp^*_{rf}, due to the rf system operating with a waveform $V_0\sin(sh/R)$, on the other hand, is given by (using Eq. (5)):

$$\Delta p^*_{rf} = \frac{heV_o}{\beta\gamma c}\frac{s}{R} \tag{8}$$

where V_0 is the rf amplitude, and h is the harmonic number. We have assumed short bunches (i.e. $hs/R \ll 1$).

We can then, following our assumption of a stationary bunch, set $\Delta p^*_{SC} + p^*_{rf} = 0$ and solve for $dI(s)/ds$:

$$\frac{dI(s)}{ds} = \frac{\beta\gamma h}{4\pi\ln(r_v/r_b)}\frac{eV_o}{Mc^2}\frac{ec}{R^2 r_p}s \tag{9}$$

Equation (9) can then be integrated to yield the parabolic current distribution, $I(s)$:

$$I(s) = \frac{\beta\gamma h}{8\pi\ln(r_v/r_b)}\frac{eV_o}{Mc^2}\frac{ec}{r_p}\frac{L_B^2 - s^2}{R^2}, \quad |s| < L_B$$
$$= 0, \quad |s| > L_B \tag{10}$$

where L_B is the full bunch half width, and we have used the constant of integration to set the beam current to zero at the end of the bunch.

Consequently, a parabolic beam distribution could possibly be stable. We also note that the central portion of a Gaussian distribution is parabolic.

To see whether this model is at all sensible, we integrate the current distribution to find the total current and a relation between the average current and the bunching factor:

$$I_{DC} = \frac{h}{\pi R}\int_0^{L_B} I(s)\,ds$$
$$= \frac{9\pi\beta\gamma}{32h\ln(r_v/r_b)}\frac{eV_o}{Mc^2}\frac{ec}{r_p}B_F^{-3} \tag{11}$$

where $B_F \equiv \dfrac{3\pi R}{2hL_B}$

We note that the bunching factor, B_F, (see section I.C) is equal to the FWHM time spread divided by the rf period to within 10% for either a Gaussian or parabolic distribution.

VI.B. Numerical example and discussion

For an example we take a 100 μA, 45 MeV proton beam bunched on the first harmonic with an rf amplitude of 50 V in the IUCF Cooler which has a circumference of 87 m. Eq. (11) predicts an equilibrium bunching factor of 9.2 for $\ln(r_v/r_b) = 5$. A rough measurement of the bunching factor for these parameters yielded a value of 12.9. In general, rough measurements of the bunching factor agree with this model to about 20%.

At this point these ideas are still pure conjecture. However, the fact that the predictions are so close to what is observed sparks some interest. The discrepancies between the measurement and model may be accounted for by differences in the actual and assumed values for $\ln(r_v/r_b)$. This model also provides a mechanism to explain why we do not observe the expected decoherence of longitudinal oscillations in the ring (i.e., the bunch is stationary), as well as an explanation for the long decoherence time of transverse oscillations (i.e. the beam momentum spread may be significantly lower than we have estimated in the past).

Even if this model is not exactly correct, some similar model is necessary in order to account for the large ratio of beam rest frame potential energy to *apparent* longitudinal kinetic energy, and the ratio of space charge force to rf force. Other, less probable, explanations for the long decoherence times being explored include effects arising from intrabeam scattering or the excitation of high frequency cavity structures in the ring by the beam.

In some future beam development period we will make careful measurements of both the beam bunch shape and bunching factor as a function of intensity and rf voltage while operating in the mode where no decoherence of large amplitude longitudinal oscillations are observed. The bunch length should oscillate about the stable beam size. It should be possible to induce these oscillations by stepping or modulating the rf amplitude; these oscillations can be measured as a test of this model.

This model is of course only applicable to high intensity electron cooled beams.

V. THE USEFULNESS OF BEAM DIAGNOSTIC SYSTEMS

V.A. Editorial comments

The usefulness of a beam diagnostic system for an accelerator operator does not increase linearly with the effort put into it. My impressions of this phenomenon are summarized in Table I. For example, let us suppose we install a wire scanner at the output of the cyclotron preceding a complex beamline. A beam physicist might use this device during a study period and, per chance, find something interesting which could lead to an improvement in operations. The second step would be to install a convenient operator interface. Then its usefulness at least triples: the operators will learn how the beam looks when things are "good" and use this diagnostic as feedback to help achieve this "good" state; operations will certainly benefit. One could then take the final significant step: why not have the computer automatically scan a preceding quadrupole, measure the beam emittance, and then adjust upstream quadrupoles so that the beam emittance entering the line is just as it ought to be?

Table I. Percentage of the potential usefulness of a beam diagnostic system which is achieved as a function effort.

Diagnostic System Components		
	Work	Usefulness
Hardware	45%	10%
User Interface	15%	30%
Expert System	40%	100%

In many respects, at IUCF we are still in stages I and II:

--We have a system which allows the tracking of a single beam bunch in 6 dimensional phase space, yet the operator doesn't know what the tune is, let alone have a system to automatically measure and correct the tune during a ramp.

--We can measure and display the beam position in the Cooler with a precision of 50 μm and bandwidth of 100 kHz, yet the operator does not have a fool-proof user-friendly method of correcting the closed orbit.

On the other hand, we are beginning to make the first steps to create a self-tuning accelerator system. In the following two sections I summarize some of these activities.

V.B. Recent and future hardware developments

Some of the work completed since the last cyclotron conference includes:

--The addition of gridded klystron pre-bunchers to both ion source high voltage terminals. The rf systems for these bunchers are phase-locked to the beam. The use of these systems has increased the beam transmission efficiency through the cyclotrons from a nominal value of about 1.5% to as high as 9%, as shown in Figure 3.

--An rf phase feedback system has been installed in the Cooler. This system allows nearly perfect transmission efficiency. Without this system, acceleration is nearly impossible.

--A transverse beam damping system has enabled a 4 fold increase in the amount of coasting beam which can be stored in the cooler.

The these projects, which have all enhanced operations, share one common feature: feedback from the beam to control a device. We are now trying to use diagnostic systems for feedback on a much broader scale.

Another project under development is a digital signal processor system which takes data from the phase space tracking system and calculates the tune. A phase-locked loop, locked to the beam, will allow the digitizing system to accurately sample the beam even for currents as low as a few tens of nA even during acceleration. This system will give the operators an online-tune measurement, and allow tracking of the tune up the ramp: a measurement which has not been made in several years. Of course, the

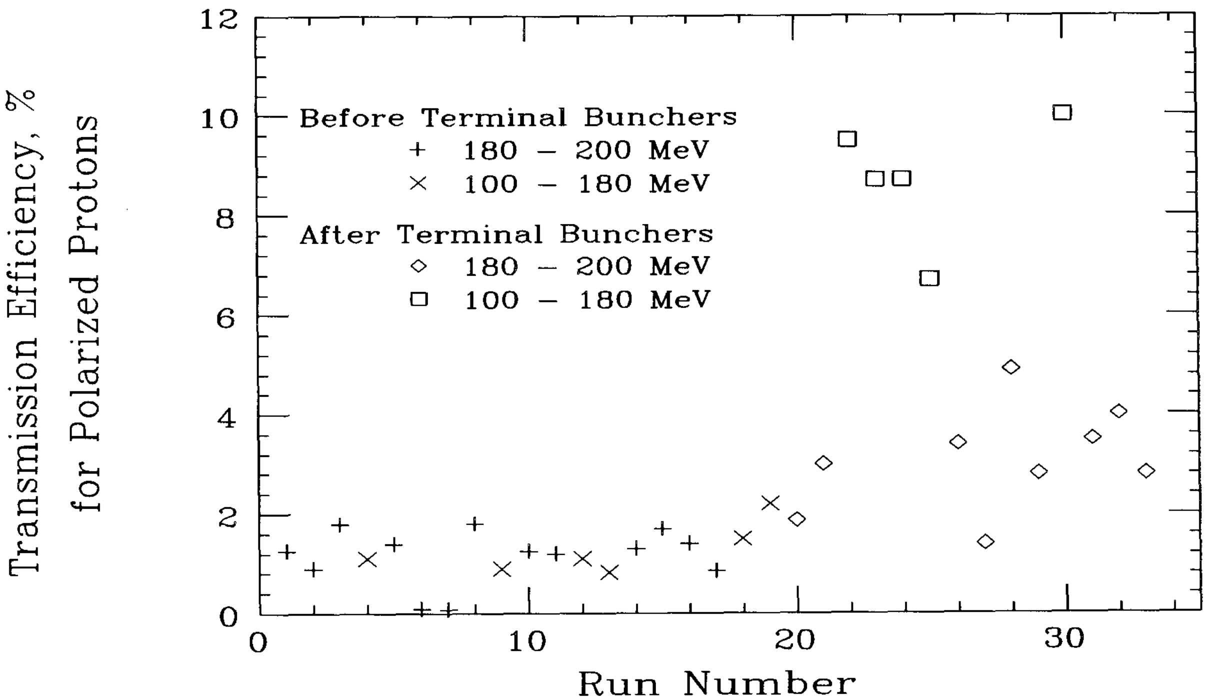

Figure 3. Effect of terminal bunchers. The numbers are from the operations logbook, not "typical" results obtained during beam studies.

next step will be to have the computer correct the tune the tune during the ramp using this system.

Also in the Cooler a system is being developed to automatically measure the influence matrix: the effect each steerer has upon each BPM. This matrix will be inverted (or used in a multi-linear regression, or chi-squared minimization program) to correct the beam closed orbit.

V.C. Diagnostic feedback systems for a new beam transport line

A new 30 m beamline is under construction to transport a 0.6 MeV beam from the new high intensity polarized ion source[16] to the cyclotrons. The beam diagnostic systems for this line is our most ambitious project yet: beam feedback will be used to provide a unique error signal for *every* device in the beamline. This includes all quadrupoles, dipoles, steerers, and buncher amplitudes and phases. Here I briefly outline this system; a more thorough report can be found elsewhere in these proceedings[17].

V.C.1. Transverse beam diagnostic feedback systems

The basis of this system will be a new beam position monitor (BPM) system. The hardware, all contained on a single 4-layer board, will accept signals from 4 electrodes and calculate the beam horizontal and vertical position, intensity, and quadrupole moment at 100 kHz rates.

An automatic emittance measurement system will measure the beam phase space ellipse at the entrance to the line. A beam scanning system will then sweep the beam centroid along an ellipse of the same shape but reduced area. Consequently, the BPM system can monitor the beam envelope[18]. Linear combinations and ratios of the beam envelope at various BPM locations will provide polar-error signals for linear combinations of quadrupoles. There will be similar systems for automatic steering and dispersion correction. We also hope to implement an automated "pencil" beam scanning system to map the acceptance of the injector cyclotron.

V.C.2. Longitudinal beam feedback systems

The new wideband ramp-waveform terminal buncher and resonant beamline bunchers will be phase-locked to beam. Their amplitudes will be set using a Bunching Factor Diagnostic (BFD) to optimize the bunching factor. A feedforward system, using a nonintercepting beam intensity monitor (BIM), will adjust the buncher amplitude to compensate for space charge effects. We are also exploring installing amplitude and phase modulators with synchronous detectors using the BFD and BIM, respectively, to set the quiescent phases and amplitudes.

ACKNOWLEDGEMENTS

The beam diagnostic system hardware design and construction discussed in this paper is being principally performed by Mark Ball and Brett Hamilton in the IUCF Beam Dynamics Group. I look forward to them reporting on the success of their efforts at the next cyclotron conference.

IUCF has a noble tradition for accomplishing great things with little more than a single Simpson meter as a beam diagnostic system; consequently, we are warily treading on new ground. The impetus for creating an expert system approach has resulted from discussions with Derek DuPlantis, John Collins, Bill Jones and Dennis Friesel. To accomplish our goals we will be relying heavily on the entire IUCF technical staff.

Many thanks to Dave Caussyn for enjoyable discussions, and for his comments on this paper. I am also grateful to Peter Schwandt for his editorial comments.

ADDENDUM

Note: a number a minor misprints in the preprint were corrected in this final version, though none affect the conclusions. It was also pointed out to me at the Cyclotron Conference by Dag Reistad (Uppsala) that the dependence of the beam bunch-width on beam current is discussed in an Appendix to a preprint submitted for publication[19].

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