Space Charge Effects and Intensity Limits of Electron-Cooled Bunched Beams

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For stripping injection of proton beams in the IUCF Cooler, electron cooling permits us to accumulate beam currents several times higher than what can be obtained without cooling. Paradoxically, the electron cooling system also appears to be responsible for limiting peak currents in the ring at 45 MeV to about 6 mA. Thus the tool which allows us to accumulate beam also prevents us from accumulating more beam. At this point we can account for some of the observed beam features when we include space charge effects. Presently, we do not, however, have any techniques to counteract the space charge effects and thus raise this intensity limit.

I. INTRODUCTION

The IUCF Cooler[1], an electron cooling[2] storage ring-synchrotron of a 3.6 T·m maximum rigidity, has been operating, primarily for internal target experiments in nuclear and particle physics, since 1988. The low beam current from the IUCF cyclotrons used for injection requires a current gain by beam accumulation of order one thousand to obtain useful event rates in experiments. The typical cyclotron beam current is about 0.5 µA. The time microstructure is a stream of 0.4 ns pulses normally spaced at 1/6 of the Cooler circumference (86.8 m). The cyclotron beam normalized rms emittance is about 1π mm·mrad and the relative rms momentum spread about $3\cdot10^{-4}$. To fill the Cooler ring, a beam pulse of 5 ms duration is diverted down the Cooler injection line by a splitter magnet with timing and repetition rate selected by the Cooler operator. At 0.5 µA, a 5 ms pulse of H_2^+ after stripping is expected to deliver about 3×10^{10} (5 mA) protons into ring. In practice, however, it takes up to 50 such pulses to reach the current of 5 mA. The maximum cooled proton beam peak current stored in the IUCF Cooler at 45 MeV is about 6 mA (i.e., 6 mA coasting beam or about 1 mA for rf bunched beams with bunching factor $BF = I_{peak}/I_{average}$ of about 6). These currents have been obtained using a combination of stripping injection of a 90 MeV H_2^+ beam with electron cooling accumulation and transverse damping. This paper elaborates on this accumulation inefficiency as well as on the cooled beam intensity limitations[3].

II. INTENSITY LIMITATIONS

A. Peak Current Limit

As might be expected, the intensity limit in the IUCF Cooler is a peak current (I_{peak}) limit, rather than an average current (I_{ave}) limit. Since to first order we expect the bunch length to vary as $I_{ave}^{1/3}$ in the space charge dominated regime[4] for a constant rf voltage, V_{rf} , it can be easily shown that for a constant peak current I_{ave} should vary as $(h/V_{rf})^{1/2}$, where h is the harmonic number. Such is indeed the case in the Cooler, as illustrated in Fig. 1, where the measured maximum-achievable average beam current is plotted as a function of the h = 1 rf voltage.

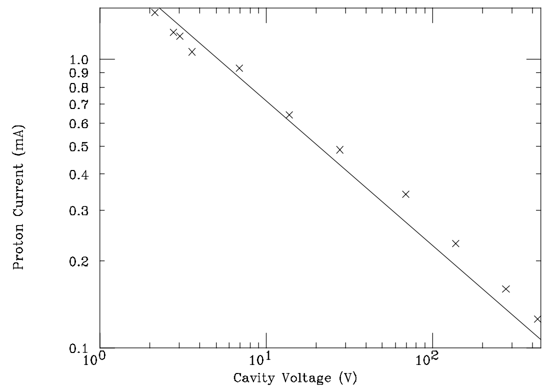

Figure 1. I_{ave} vs. V_{rf} (h = 1) in the IUCF Cooler. Solid line is $V_{rf}^{1/2}$.

This suggests an operating mode which would increase I_{ave} without actually addressing the I_{peak} limit: for highly cooled beams, the balance between the space charge and rf forces determines the required rf voltage for fixed frequency operation and the required energy gain per turn determines the voltage requirements during ramping. This is in contrast to the bucket area ($\propto h^{-1/2}$) requirements for emittance dominated beams in many other machines. We thus operate in a regime where the required V_{rf} is not a function of h for beam acceleration, and should be able to increase I_{ave} by a factor of 2 to 3 by operating with a larger value for h (we presently operate at h = 1 for historical reasons).

B. Coherent Transverse Instabilities

Although coherent transverse instabilities have been observed, they do not appear to be a limit:

--Coherent transverse instabilities are usually observed only when the Cooler is operated in a non standard mode (i.e., cooling the beam after injection for many seconds before beginning acceleration).

--A transverse feedback (damping) system can damp these instabilities at rates up to two orders of magnitude faster than the measured growth rates.

C. Injection Efficiency

The I_{peak} limit is, within limits, independent of both the injected beam current and the injection repetition rate. We thus conclude that the limit is not related to beam lifetime. This is illustrated in Figure 2 which shows the stored average current as a function of time during the process of cooling

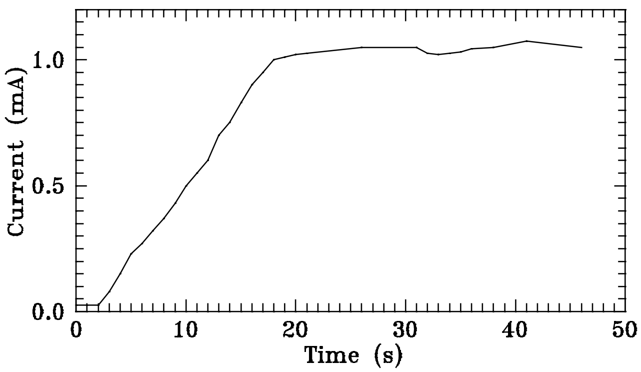

Figure 2.Beam current as a function of time during continuous stripping injection with cooling accumulation. $V_{rf} \approx 10$ V.

accumulation using stripping injection. The beam current does not increase as $I_{limit}(1 - e^{-t/\tau})$, where τ is the beam lifetime; rather the current increases with no significant change in rate until just below the limiting current. Beam is lost continuously between injections rather than suddenly; thus there is no indication of an easily-correctable hardware problem. The manner in which the beam approaches its limiting current can be explained by the beam lifetime being a highly nonlinear function of the beam intensity.

D. Increased Transverse Beam Size

One could conjecture that the intensity limit is due to an increase in the beam size with increasing current. This conjecture was verified by measuring transverse beam profile using a new "flying wire" profile monitor installed in the

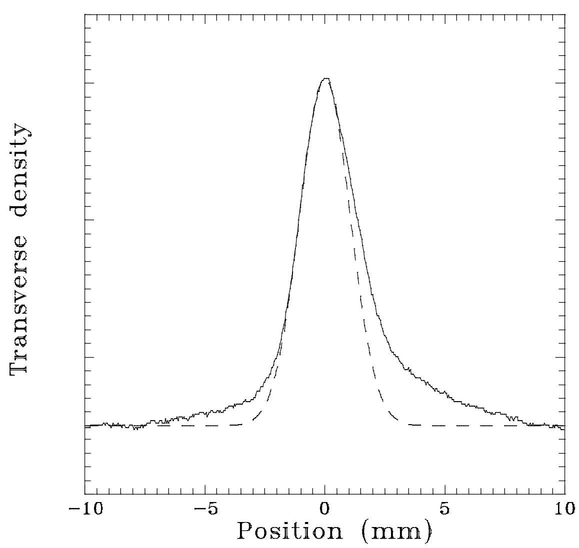

Figure 3. Transverse beam profile (solid) and Gaussian fit (dashed). Average (peak) beam current: 460 (2,000) µA; rms size from the fit: 1.05 mm.

region of the Cooler where the dispersion function is nominally zero and the measured horizontal beta-function is 13.2 m. A rotary pneumatic actuator swings a 6.4 µm diameter carbon filament through the beam at a speed of 8.1 m/s. Secondary electrons produced by the protons passing through the filament are collected by an electrode surrounding the fiber holder. This current is amplified by a low-noise current-to-voltage converter, recorded by a digitizing oscilloscope, and transferred to storage on a PC for offline analysis. Approximately 200 to 500 beam revolution periods are necessary to measure the profile, and consequently the monitor cannot differentiate between coherent betatron oscillations and the beam size due to incoherent oscillations.

Figure 3 is an example of a transverse beam profile. The long tail on the right-hand side of the profile is due to the interaction of the wire with the proton beam. One can also observe a relatively long tail on the left-hand side. This tail corresponds to an emittance ≈60 times larger than the rms emittance of the bright central core; such tails develop for relatively high (> 1−2 mA) peak beam currents and are believed to be related to the beam intensity limit in the IUCF Cooler.

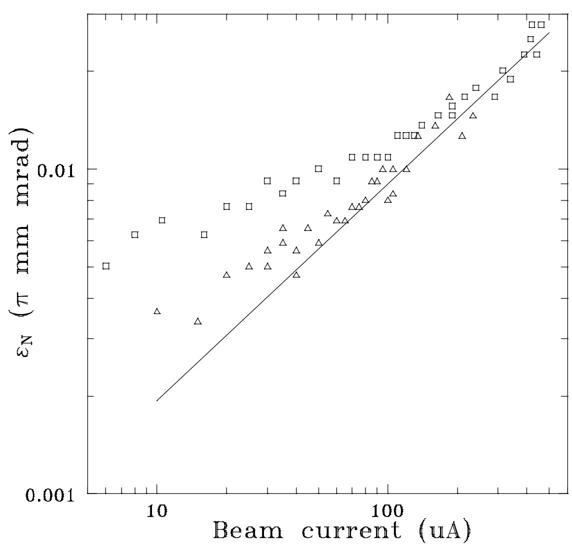

Figure 4. Normalized rms emittance as a function of the average bunched proton beam current before (□) and after (△) the alignment of electron and proton beams. Solid line is $I^{2/3}$.

Recent measurements of the transverse beam size as a function of beam current indicate that even at high currents the non-normalized emittance (≈ 0.1π mm·mrad) is still only a small fraction of the ring acceptance (≈ 15π mm·mrad). Figure 4 shows the measured equilibrium horizontal rms normalized emittance as a function of the average beam current. Note that the measurements were made with bunched beams and that the horizontal scale is the average beam current. One observes that the beam size varies approximately proportional to the 1/3 power of the beam current. Since the bunch length, to first order, also varies as the 1/3 power of the beam current, we see that the particle beam density to first order stays constant as does the ratio of the longitudinal and transverse beam temperatures.

E. Space Charge Effects

The peak current limit appears to be due to space-charge effects. Space-charge effects in synchrotrons are usually quantified by the space-charge tune shift, ΔQ_{SC} which can be expressed as:

$$\Delta Q_{SC} = \frac{BF \cdot I_{ave} C\, r_p}{4\pi e c \beta^2 \gamma^2 \varepsilon_N} , \qquad \textbf{(1)}$$

where C is the ring circumference, r_p is the classical proton radius, e is the proton charge, c is the speed of light, β and γ are the usual relativistic parameters, and ε_N is the normalized rms beam emittance. ΔQ_{SC} is the amount the incoherent betatron tune is reduced due to defocusing effects from the beam space charge. Note that ΔQ_{SC} is not directly measured; in this case the tune shift is a mathematical quantity which can be exactly calculated but does not necessarily accurately represent what is happening physically. Fig. 5 shows this calculated space-charge tune shift as a function of a 45 MeV proton beam current.

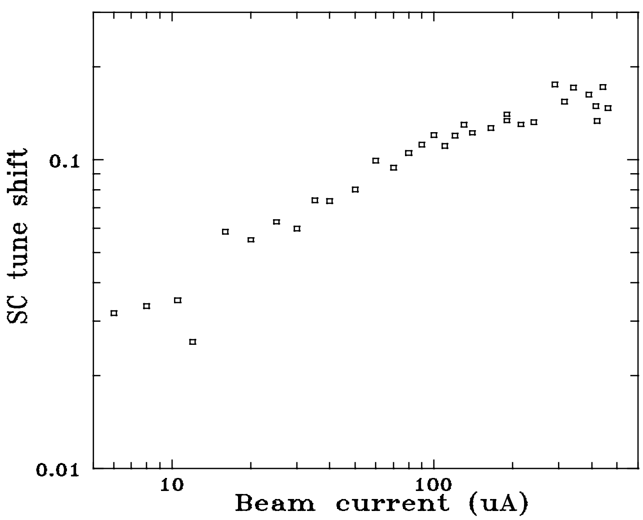

Figure 5. Space charge tune shift as a function of I_{ave}.

It is easy to understand how a large ΔQ_{SC} can lead to emittance growth: the small amplitude particles, which have the largest tune shift, can be shifted onto major resonance lines. It is less easy to understand why a large tune shift should lead to beam loss. It may be that particles with large amplitudes are lost; these particles experience a smaller tune shift, but also experience more nonlinear fields from the beam space charge which may drive higher order resonances.

We have observed that very small (< 0.01) changes in the coherent betatron tunes ($Q_x \approx 3.8$, $Q_y \approx 4.8$) can cause more than order of magnitude changes in the equilibrium beam intensity; this is somewhat unexpected for situations in which the incoherent tune shift is presumed to be more than an order of magnitude larger.

One of the mechanisms which could be responsible for this current limit is a halo formation[5]. Both non-uniform transverse density distribution (Fig. 3) and periodic density fluctuations of the cold beam core due to changes in beta-functions could be a halo-producing mechanism. According to computer simulations[5] large energy transfer can occur in a single interaction of the particle with the cold core, thus the particle with initial betatron motion can be slowed, stopped, or accelerated in one betatron oscillation period. However, the subject of halo formation is not yet well understood, especially in systems where space charge and emittance play approximately equal roles. Nevertheless, one could make a cautious suggestion of how to possibly avoid the losses if they were associated with the halo formation. One suggestion for future machine designs is to make the machine lattice functions smooth in order to avoid large periodic density fluctuations. Another suggestion is to increase the emittance of the cold core by, perhaps, heating it in a controlled way.

F. Beam heating

Our attempts to heat the beam with white noise applied to a transverse kicker resulted only in reduced lifetime. We found that the beam lifetime is inversely proportional to the total power of applied transverse white band (50 MHz-300 MHz) noise without any noticeable changes in a transverse beam size.

One of the possible heating techniques could be a hollow electron beam created by a ring-shaped cathode. This would create a cooling-free phase space region within available acceptance. If one now places the proton beam closed orbit into this region by aligning the proton beam with the axis of the electron beam, proton beam emittance would be increased to the dimensions of this cooling-free area. Since the available acceptance is at least two orders of magnitude greater than the typical beam emittance, this technique could lead to an order of magnitude increase in the current limit.

III. CONCLUSION

Thus far, we have identified no techniques that can substantially increase the limiting beam current without compromising our ability to accumulate beam quickly by stripping injection. In the future, kick injection of beam from a new Cooler injector synchrotron[6] at significantly higher energy should reduce space charge limits. This work is supported by the National Science Foundation (Grant No. NSF PHY 93-14783).

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