COOLED BEAM INTENSITY LIMITS IN THE IUCF COOLER

Daniel Anderson, Mark S. Ball, Vladimir Derenchuk, Gary East, Michael Ellison,
Tim Ellison, Dennis Friesel, Brett J Hamilton, Sergei S. Nagaitsev, Terry Sloan,
Peter Schwandt

IUCF - 2401 Milo Sampson Ln., Bloomington IN 47405

ABSTRACT

In the case of stripping injection, electron cooling enables the IUCF Cooler to accumulate beam currents about 10 times higher than what can be obtained without cooling; in the case of kicked injection of fully-stripped beams, this ratio is greater than 1,000. Paradoxically, the electron cooling system also appears to be responsible for limiting the peak current in the ring at 45 MeV to about 6 mA; this limit is more than an order of magnitude below what we might expect without cooling. Thus the tool which allows us to accumulate beam also prevents us from accumulating more beam.

1. INTRODUCTION

The maximum cooled proton beam peak current stored in the IUCF Cooler at 45 MeV is about 6 mA (i.e., coasting beams of 6 mA, and 1 mA of rf−bunched beams with bunching factors [$BF = I_{peak}/I_{average}$] of about 6). These currents have been obtained using a combination of stripping injection with electron cooling accumulation and transverse beam damping. This performance limitation appears to be similar to that reported at other laboratories operating with similar beams:

--The LEAR ring has stored coasting cooled beam currents of up to 3 mA using both electron cooling and dampers[1].

--CELSIUS has been able to accumulate 2 mA using the electron cooling accumulation mode of injection and dampers[2].

The *un-cooled* beam limit in the Cooler, however, may be 1 to 2 orders of magnitude higher. CELSIUS, for example, has accumulated and accelerated 40 mA (corresponding to 200 μA assuming a bunching factor of 5) using stripping injection *without* cooling[3]. This is about 40 times greater than what has been achieved at IUCF; the principal reason being the higher CELSIUS injector current, ≈ 75 μA as compared to ≈ 0.75 μA at IUCF.

At this point we do not know what causes this intensity limit, nor do we have any techniques to raise this limit. We hope that discussion of these limitations at the workshop will provide us will ideas which can bring back to IUCF. Below we summarize what we know about this intensity limit.

2. INTENSITY LIMITATIONS

2.1 Peak Current Limitation

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][5], where V_{rf} is the rf voltage, it can easily be shown that I_{ave} should vary as $V_{rf}^{-1/2}$ for a constant peak current. Such is the case in the Cooler, as illustrated in Figure 1, where we plot the measured average current as a function of the $h = 1$ rf voltage (h is the harmonic number). This does, however, suggest an operating mode to maximize I_{ave} without actually addressing the I_{peak} limit: I_{ave} should vary as $h^{1/2}$ for constant V_{rf}. Since the required bucket area for cooled beams is so small, the rf voltage requirement is almost entirely determined by the required energy gain per turn; we thus operate in a regime where V_{rf} is not a function of h, 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). Instituting a "parabola" at the beginning of ramping would also lead to increased I_{ave} without increasing I_{limit}.

2.2 Injection Efficiency

As also might be expected, the I_{peak} limit is independent of the amount of injected beam current, as well as, within limits, the repetition rate at which we inject beam. We can 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 accumulation using stripping injection. The beam current does not increase to its maximum value as $I_{limit}(1 - e^{-t/\tau})$, where τ is the beam lifetime; rather the current increases with no apparent change in rate until just below the limiting current. More detailed information on how cooling is used as an injection aid can be found in another contribution to this workshop[6].

2.3 Increased Transverse Beam Size

One could conjecture that the intensity limit is due to an increase in the beam size. Such a conjecture is supported by the large decrease in the geometrical constant g[4], which is proportional to the natural logarithm of the beam radius to the vacuum chamber radius for a centered beam inside a round pipe, as shown in Figure 3. This conjecture was tested by measuring the effective ring aperture as a function of beam current. The aperture was "measured" by exciting a coherent betatron oscillation with the injection pulse kicker magnet and observing the percentage loss of beam. The results, shown in Figure 4, however, would seem to indicate the opposite: that the available aperture in the machine *increases* with beam current! This is a mystery, and the explanation could be quite complicated. We do know that at high beam currents the decoherence of both longitudinal and transverse coherent oscillations is suppressed, so very different things happen to the beam in the low and high current regimes when a coherent oscillation is excited.

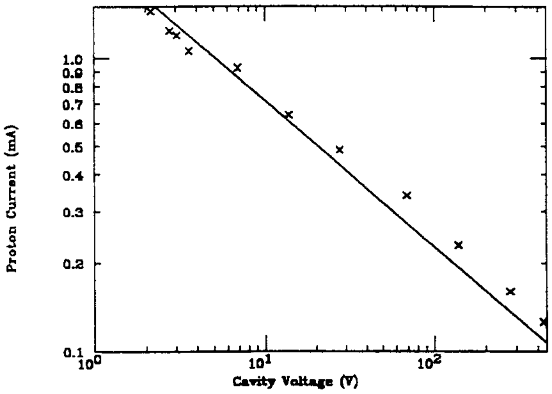

Figure 1. I_{ave} vs. V_{rf} ($h = 1$) in the IUCF Cooler. Solid line is $V_{rf}^{1/2}$.

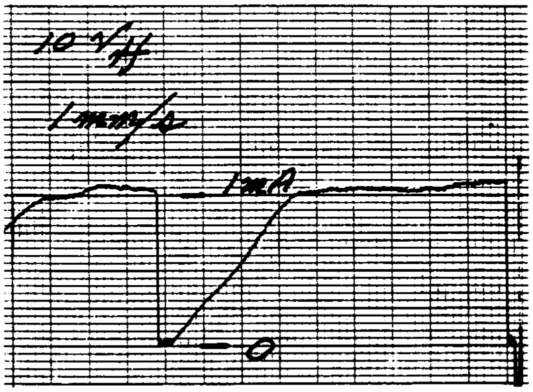

Figure 2. Beam current as a function of time during stripping injection with cooling accumulation.

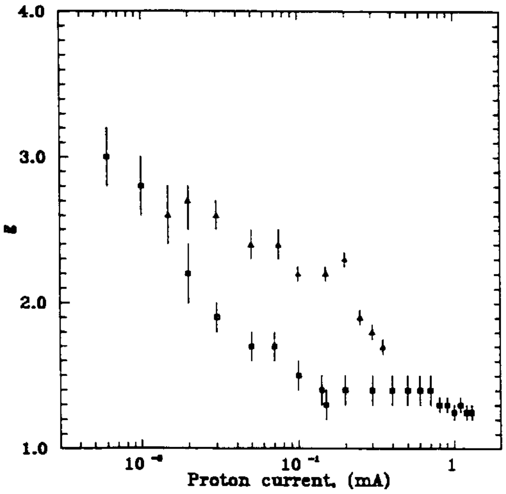

Figure 3. Geometrical constant g as a function of current.

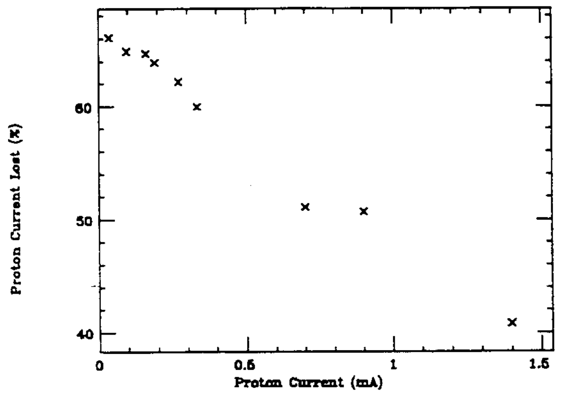

Figure 4. Percentage beam loss as a function of beam current for a fixed kicker strength corresponding to 10 $\pi\mu$m (non-normalized).

We could also conjecture that if the beam size increased substantially as the current increased, a limit might be reached due to a sudden beam loss at injection due to the stacked beam striking an aperture when the injection magnets are pulsed. This also does not appear to be the case; Figure 5 shows the stored beam current as a function of time between injection cycles. A sudden beam loss at injection is not observed; instead the beam current smoothly decreases between injection cycles.

2.4 Beam Lifetime as a Function of Intensity

The manner in which the beam intensity approaches its limiting current can be explained by the beam lifetime being a highly nonlinear function of the beam intensity. This is illustrated in Figure 6 which shows the beam current as a function of time after the injection system is turn off. However, the mechanism responsible this behavior in unknown.

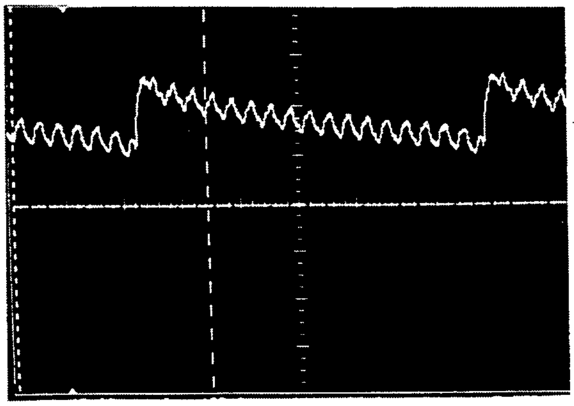

Figure 5. $I_{ave}(t)$ between injection cycles; 50 μA, 50 ms per div ($I_{ave,max}$ = 1.5 mA).

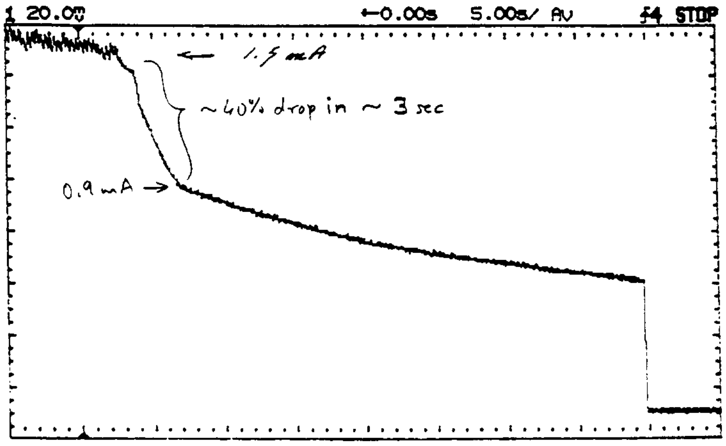

Figure 6. Beam current as a function of time after the injection system is turned off.

2.5 Coherent Transverse Instabilities

Although coherent transverse instabilities have been observed, they do not appear to be a limit[7]:

-- 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.

2.6 Space Charge Effects

The 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:

$$\Delta Q_{SC} = \frac{BF \cdot I_{DC}\, C\, r_p}{4\pi e c \beta^2 \gamma^2 \epsilon_N}$$

where I_{DC} is the average beam current, C the ring circumference, r_p the classical proton radius, e the proton charge, c the speed of light, β and γ the usual relativistic parameters, and ϵ_N the normalized rms beam emittance. ΔQ_{SC} is the amount the incoherent betatron tune is reduced due to defocussing effects from the beam space charge. We note that ΔQ_{SC} is not directly measured; the tune shift is a mathematical quantity which can be exactly calculated but does not necessarily accurately represent what is happening physically.

In order to estimate the value of ΔQ_{SC} it is necessary to measure ϵ_N ; this quantity is usually determined by measuring the beam size in a region with known beta functions. An emittance dominated model is then used to determine the beam emittance. We note, however, that as the longitudinal beam size is not a measurement is not a measurement of the longitudinal emittance, but rather the beam current, so too the transverse beam size may not be a measurement of the transverse beam emittance if the beam properties in the transverse plane are also space charge dominated. Previous measurements[8] using the emittance dominated optics model indicated that the space charge shift may be as high as 0.3, corresponding to what is typically considered to be the practical space charge limit.

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

We have observed that very small (< 0.01) changes in the coherent betatron tunes can make greater 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.

2.7 Beam Heating?

At present we have not found a technique which will preserve the beneficial aspects of electron cooling, thus allowing us to accumulate beams, while alleviating the detrimental effects (presumably very small beam emittances). In the future we will try various "heating" mechanisms, which have been tried without success in the past, though not under controlled conditions.

In the past we have tried heating the beam using white noise applied to a transverse kicker. To first order there was no change in the beam emittance (as measured by a "flying beam" scanner) but a large change in the beam lifetime. At high intensities we found this noise, to first order, merely excited coherent transverse instabilities and decreased the beam current. It turns out to not be such an easy problem to increase the beam emittance -- at high intensities, coherent oscillations tend not to decohere as rapidly as would be expected with an emittance dominated beam. In the future we will try using high frequency white noise (such that the beam wavelength is much longer than the noise wavelength) in conjunction with a coherent transverse damping system. The equilibrium proton beam emittance can be increased by mis-aligning the electron and proton beams in the cooling region[9] (Figure 7). We have demonstrated that the highest stored beam currents are obtained when the electron and proton beam are *not* exactly aligned so as to maximize the measured cooling forces. We do not, however, think that there is a lot to be gained here -- the operators routinely use the stored beam current as feedback in adjusting the beam alignment.

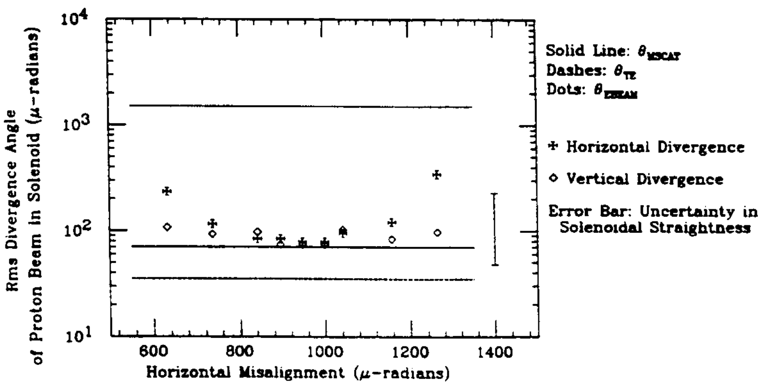

Figure 7. Proton beam H and V angular divergences in the cooling region vs. the H angular alignment between the beams.

We will also try heating the beam using multiple scattering from an internal target, though we do not expect this technique to have great potential. One can show that, for a zero-emittance beam, the small angle multiple scattering beam lifetime is ≈ 0.2Z/(Z + 1) times the single scattering lifetime. We would consequently expect that the single scattering lifetime will be ≈ 0.1 s × A/ϵ_{eq} where A is the ring acceptance and ϵ_{eq} is the equilibria emittance.

3. CONCLUSIONS

We have just begun to explore means for increasing the stored beam limitations. Thus far, we have identified no techniques which can substantially increase the limiting beam current without compromising our ability to quickly accumulate beam. There are many unanswered questions and mysteries. In early November we will systematically explore the beam transverse equilibrium using a flying wire profilometer; the information from this monitor should answer many of our question. In the meantime, we are beginning to take more seriously the possibility of drilling a small hole in the center of the cathode!

ACKNOWLEDGEMENT

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