Beam Property Measurements in the IUCF Cooler Ring

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Abstract

The high intensity stored beam stability limits of the IUCF Cooler-Storage Ring are being explored. Measurements of the equilibrium emittance and bunching factor for a 45 MeV electron cooled proton beam as a function of stored beam intensity are reported. In addition, calculations of space-charge tune shift based on these measurements are presented. The tune shift is found to be as large as about 0.3 in magnitude, depending on the degree to which the beam is cooled. The space-charge tune shift is discussed as a possible contributing factor to observed stored beam current limits.

I. Introduction

The Indiana University Cyclotron Facility Cooler Storage Ring and synchrotron accelerator ($B\rho$ = 3.6 Tesla meters) was proposed in 1981, funded for construction in 1983, and completed in 1987. It was the first of the many similar accelerator storage rings designed specifically to employ electron cooling to produce and use high quality medium energy ion beams in equilibrium with thin internal targets for nuclear research. The status and development of the IUCF Cooler ring[1, 3], and cooling system [2, 4] have been reported in numerous accelerator conference proceedings.

We have accumulated 45 MeV proton beams in the Cooler using stripping injection of 90 MeV H_2^+ beams; further accumulation is possible using the electron cooling system to coalesce the injected beam into a stack such that the process can be repeated. We have observed coherent transverse instabilities for these low emittance, low momentum spread electron cooled beams near the maximum attainable beam currents, about 1 – 4 mA for coasting beams. However, intensity limits are also reached at nearly the same current, but with no observable coherent transverse instabilities. Clearly, in addition to coherent transverse instabilities at least one other process limits the beam current. We hypothesize that one such additional limitation is due to the space-charge tune shift. In this work, we explore this hypothesis by using measurements of the bunching factor and the beam emittance to calculate a space-charge tune shift.

II. Procedure and Results

The bunching factor, B_f, is a measure of the peak-to-average beam current. Assuming that the beam distribution is Gaussian, we define B_f (> 1) by

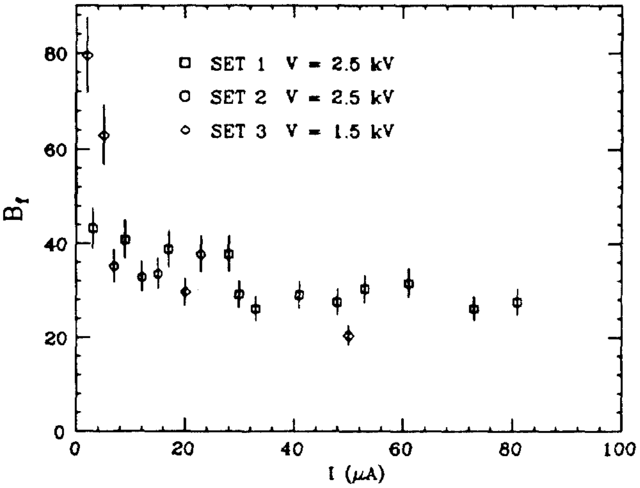

Figure 1: Plot of typical values of the bunching factor versus beam current. The three different data sets correspond to data taken for three different machine conditions. In each case, the rf harmonic number is 6, and the rf cavity voltage, V, is listed.

$$B_f = \frac{\tau}{\sqrt{2\pi}\sigma_t}, \qquad (1)$$

where τ is the rf period, and σ_t is the time width of the beam. The value of σ_t was measured from the oscilloscope trace of the signal from the beam position monitor (BPM), or a low bandwidth or high bandwidth wall gap monitor[5], which ever of the three had the most suitable bandwidth for the beam pulse width. The B_f for three different sets of data taken are plotted as a function of beam current in Figure 1. Each data set corresponds to a slightly different machine tune and, qualitatively, increasingly better cooling in going from the first to the third set. Generally, we observed that the B_f decreases with increasing beam current and does not appear to have a strong dependence on the quality of the electron cooling.

The horizontal transverse emittance, ϵ_x, is found from the beam profile. The profile was determined by horizontally sweeping the beam through a profile monitor, a vertically-mounted 10 μm diameter carbon fiber, and measuring the secondary emission current using a high input impedance amplifier. The profile monitor was mounted in a region of high momentum dispersion (4 m) where the horizontal motion of the beam was generated by ramping the

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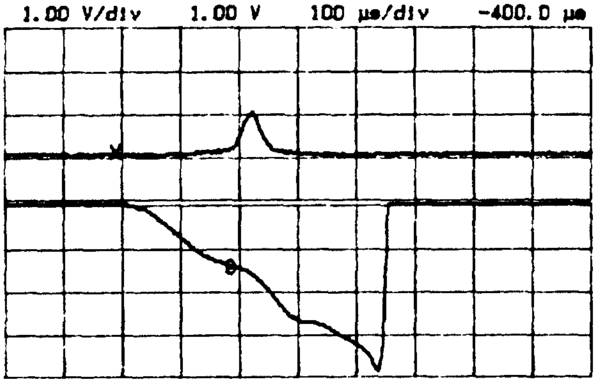

Figure 2: Typical oscilloscope traces of the beam profile monitor current (top trace) and the position signal from a Beam Position Monitor (bottom trace, delayed by 15 μsec). Horizontal scale is 100 μsec, and the BPM vertical scale is 2.1 mm/div. The slight oscillation in the BPM output is due to synchrotron oscillations.

rf cavity frequency. The transverse velocity of the beam while measuring the profile was as high as 19 m/sec in this region. Both position of the beam centroid, measured using a nearby BPM, and the secondary emission current from the profile monitor were recorded simultaneously as functions of time (see Figure 2). The width of the beam profile, σ_x can then be easily determined from these two plots.

The value of σ_x includes a contribution due to betatron oscillations,$\sigma_{x\beta}$, and another due to the beam momentum spread and the ring dispersion, σ_{xp}. The value of σ_{xp} is found from,

$$\sigma_{xp} = \eta \frac{\Delta p}{p}, \tag{2}$$

where η is the dispersion function. For small oscillations,

$$\frac{\Delta p}{p} = \frac{\nu_s}{\eta_0}\sigma_t \tag{3}$$

with

$$\eta_0 = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}. \tag{4}$$

In these expressions, γ and γ_t are the relativistic factors associated with the beam energy and the transition energy respectively ($\gamma_t = 4.85$), and ν_s is the synchrotron frequency.

For an electron cooled proton beam, the Fokker-Planck equation gives basically a Gaussian distribution in the six dimensional phase space. In this case, the rms beam size is given by the Gaussian quadrature of the components from momentum and position space. So, the broadening due to the momentum dispersion can be removed,

$$\sigma_{x\beta} = \sqrt{\sigma_x^2 - \sigma_{xp}^2}. \tag{5}$$

Then, the transverse emittance is calculated using the relation, $\epsilon_x = \sigma_{x\beta}^2/\beta_x$, where β_x is the betatron amplitude function ($\beta_x = 2.0$m). Due to uncertainties in the momentum spread, this determination of ϵ_x is not as precise as could be accomplished with a flying wire profile monitor in a dispersion free region.

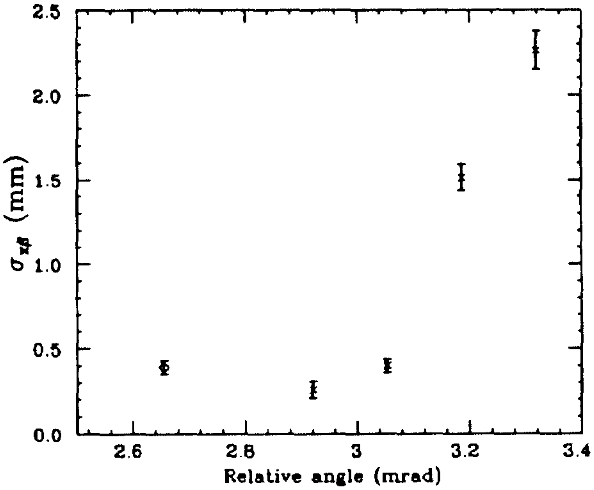

Figure 3: Plot of the rms beam width due to betatron oscillations versus relative angular misalignment of the proton and electron beams in the cooler region. Note that the location of the origin for the angular misalignment is arbitrary.

In Figure 3, $\sigma_{x\beta}$ is plotted versus the relative angular misalignment of the electron and proton beams in the electron cooling region. The misalignment was produced by "tilting" the magnetic field lines in the cooling region solenoid by varying the strength of a superimposed horizontal dipole magnetic field. The data plotted in this figure are for a proton beam current of about 60 μA and a B_f of about 30. All the data in this figure were taken with identical operating conditions with the exception of the point marked with a diamond for which there is an additional insignificant vertical misalignment. It is clear from this figure that ϵ_x is a strong function of the electron cooling. In fact, for a large part of the range covered by the data, the equilibrium proton beam rms divergence in the cooling region is to good approximation the angular misalignment between the electron and proton beams. This would be akin to the monochromatic instability[7]. It should also be noted that, based on this figure, we have determined that none of the three data sets used in the rest of this work were taken with minimum misalignment and, consequently, minimum emittance.

In Figure 4, values of ϵ_x are plotted as a function of beam current for each of the three sets of data taken. As in the discussion of the bunching factor, the electron cooling is improved in moving from the first to the third data set. With a possible exception for beam currents less than 20 μA, ϵ_x generally increases with beam current. There is also a systematic decrease in emittance in going from the first to the third data set corresponding to improved cooling.

Assuming that the beam is on-axis in a circular chamber with negligible effects due to image charges and currents,

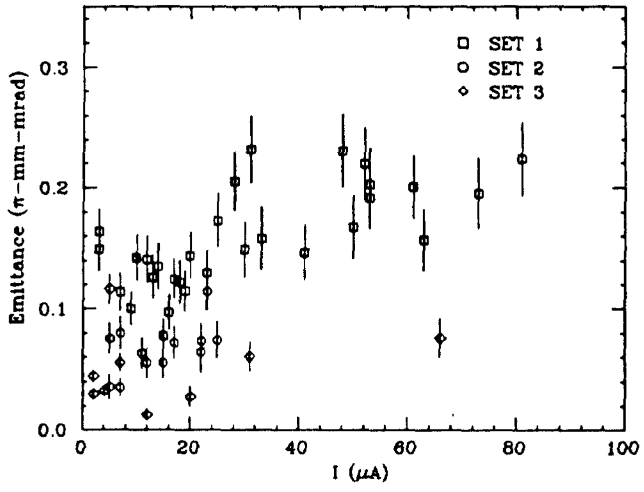

Figure 4: Plot of the radial transverse emittance versus beam current for data taken with three slightly different operating conditions.

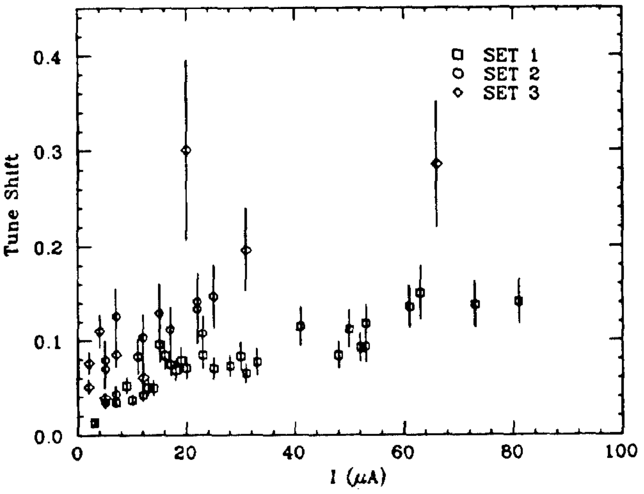

Figure 5: Plot of calculated space-charge tune shift versus beam current.

the space-charge tune shift is calculated from [6],

$$\nu_{sc} = -\frac{NRr_p}{\pi\nu_x\gamma^3\beta^2}\frac{B_f\beta_x}{4\epsilon_x}. \qquad (6)$$

In this expression, N is the number of particles in the ring, R is the ring radius, r_p is the classical proton radius, ν_x is the horizontal betatron tune of the cooler ring, and β and γ are the usual relativistic factors. The ν_x for the ring was measured using the ping-tune method [5], and was about 3.8.

Values calculated for the magnitude of $\Delta\nu_{sc}$ are plotted versus beam current in Figure 5 for each of the three data sets discussed previously. In this figure it is evident that $|\Delta\nu_{sc}|$ monotonically increases with beam current. It is also clear that as the cooling is improved, the values of $|\Delta\nu_{sc}|$ are greater at each current. It is also suggestive that $|\Delta\nu_{sc}|$ increases with beam current at greater rates as cooling is improved.

III. Conclusions

We have found that the transverse emittance is very sensitive to the angular alignment between the electron and proton beams within the electron cooling region. The longitudinal emittance, as evidenced by the bunching factor, is less sensitive.

Over the range of stored beam currents explored here, we have seen calculated space-charge tune shifts in a broad range, but increasingly large when the misalignment between the electron and proton beam is minimized. The magnitude of the observed tune shifts were as large as 0.3 with the best cooling. With higher currents and optimized cooling, larger space-charge tune shifts are expected. With tune shifts of this magnitude, it is evident that space charge is indeed a factor in stored beam current limitations observed in the IUCF Cooler Ring. Additional studies in which the beam lifetime corresponding to these large tuneshifts is measured, and more precise measurement of emittance is made, would be useful.

At IUCF our goal is to increase the luminosity by an additional two orders of magnitude to 10^{32} s^{-1}-cm^{-2}. Consequently, we will be adding active damping systems and other systems which will enable us to use the advantages of electron cooling to accumulate high intensity beams while avoiding the low momentum spreads and emittances which limit the intensity due to coherent transverse instabilities and the space charge tune shift.

References

[1] R.E. Pollock, "IUCF cooler ring status 1989", *Proc. 1989 IEEE P.A.C., Acc. Eng. and Tech.*, Chicago, IL, pp. 17-21.

[2] Timothy JP Ellison,Dennis L. Friesel, and Robert J. Brown, "Status and performance of the IUCF 270 keV electron cooling system", ibid, pp. 633-635.

[3] D.L. Friesel, T.J. Ellison and P. Schwandt, "Status report on the IUCF cooler-storage ring" *Nucl. Inst. Meth.* **B40/41**, 927-933 (1989).

[4] T. Ellison, "Electron Cooling", Indiana University, Bloomington, Indiana, Ph.D. Dissertation, 1990 (unpublished).

[5] Mark Ball, Timothy JP Ellison, and Brett Hamilton, "Beam diagnostic systems in the IUCF cooler ring", This conference.

[6] B. Zotter, "Betatron frequency shifts due to image and self fields", in *CERN Accelerator School, General Accelerator Physics*, eds. P. Bryant, S. Turner, CERN 85-19, p. 253

[7] Ya.S. Derbenev and A.N. Skrinsky, "The kinetics of electron cooling of beams in heavy particle storage rings", *Particle Accelerators*, **8**, pp. 1-20 (1977)