ANALYSIS OF BEAM PROFILE BROADENING AT HIGH INTENSITY IN THE PSR ACCUMULATOR RING

J. A. Holmes, A. Aleksandrov, J. D. Galambos, D. K. Olsen
SNS Project, Oak Ridge National Laboratory, Oak Ridge, TN 37831-8218
F. Merrill, and R. J. Macek
Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

Beam profile measurements taken after extraction from the Proton Storage Ring (PSR) at Los Alamos National Laboratory show significant broadening in the vertical direction at high intensities for bare tunes near $\nu_y = 2.14$. Careful simulations of the injection, accumulation, and extraction yield good agreement with the measured beam profiles. In both experiment and simulations, raising the bare tunes even slightly reduces the profile broadening. Simulations show that the addition of second harmonic RF focusing reduces the transverse beam broadening. When second harmonic RF focusing is combined with raised bare tunes in the simulations, the beam profile broadening is negligible. Analysis shows that the vertical broadening is a result of the beam envelope in resonance with the lattice at precisely four envelope oscillations per turn. These results suggest that high-intensity beams can be well contained in accumulator rings through a proper choice of operating tunes, injection scheme, and RF focusing.

1 INTRODUCTION

Space charge contributions to beam loss are an essential concern in high intensity rings that are characterized by large beam currents and by stringent uncontrolled beam loss requirements. A number of computer codes have been developed to study this problem [1-4]. These codes track particles through the periodic ring lattice in the presence of space charge forces, which places stringent numerical requirements on the computational representation [5]. There has been some success in benchmarking different beam dynamics codes for high-intensity rings with respect to each other [6]. A careful simulation of experimental data taken at the Proton Storage Ring (PSR) [7] at Los Alamos National Laboratory (LANL) has been carried out using one of these codes [8]. This work shows good agreement between the measured and calculated data, particularly in predicting the broadening of the transverse beam profile in the vertical direction at high beam intensity. The present work extends that of Ref. [8] by presenting an analysis and explanation of the beam broadening and by showing how it can be avoided.

The PSR is an ideal site to study the space charge dynamics of high-intensity rings. Space charge tune shifts are up to 0.2, compared to bare tunes of roughly $\nu_x \approx 3$ and $\nu_y \approx 2$. In the present experiments, injection was carried out for 2864 turns of accumulation yielding a maximum intensity of 4.14×10^{13} particles. Injection painting was carried out with the closed orbit at fixed horizontal displacement and angle relative to the injected beam. The vertical displacement and angle were varied during the first 825 μs. Also, the ring dispersion function is nonzero at the foil, so that the beam energy spread broadens the horizontal distribution. Immediately after injection, the beam was extracted in a single turn and transported to a beam profile diagnostic in the extraction line. This was carried out for various beam intensities and bare tune settings. One set of measurements was completed for bare tunes of $\nu_x = 3.17$, $\nu_y = 2.14$ with all parameters held fixed except for the injected particle intensity. Then the bare tunes of the ring were raised slightly to $\nu_x = 3.19$, $\nu_y = 2.17$, and the full-intensity measurement repeated.

For each beam profile measurement, a complete simulation was carried out using the ORBIT code [3]. The present calculations include detailed representations of the injection scheme, the PSR lattice, and the space charge forces. Details of the assumptions are given in Ref. [8]. Details on the physical and numerical models and issues in the ORBIT code are given in reference [5].

2 RESULTS

The present results employ the same computational assumptions and procedures as in Ref. [8]. A beam intensity scan consisting of four cases, 4.14×10^{13}, 2.07×10^{13}, 1.00×10^{13}, 0.50×10^{13} protons at bare tunes of $\nu_x = 3.17$ and $\nu_y = 2.14$, was conducted. The measured and calculated horizontal beam profiles are in good agreement, with shapes nearly independent of the beam intensity. The profiles are peaked and of fixed width. Calculations without space charge yield similar horizontal profiles that are only slightly narrower than those with space charge. Hence, space charge effects are small in the horizontal plane.

Because of the painting scheme, the vertical beam profiles are much broader than the horizontal profiles. Also, the vertical profiles are sensitive to beam intensity, broadening considerably in the highest-intensity case. This effect is nonlinear and occurs both in the experimental and the calculated results. Because space charge provides the only nonlinearities in the calculations the vertical profile broadening must be due to space charge. Comparison of the measured and calculated vertical beam profiles for the highest-intensity case shows that the calculated results with space charge agree much better with the measured profiles than do the calculations with space charge omitted. The vertical profile obtained without space charge is relatively narrow as in the low intensity cases and it is hollow because of the off-axis injection scheme. Space charge provides the correct systematics, with the profiles broadening considerably at the highest beam intensity, and there is no other mechanism in the calculations to provide such an effect.

These measurements and calculations were repeated at high-intensity for the slightly increased bare tunes of $\nu_x = 3.19$, $\nu_y = 2.17$. For both experimental and calculated horizontal profiles there is little difference caused by increasing the bare tunes. However, raising the tunes leads to a noticeable narrowing of both the calculated and measured vertical beam profiles. The broadening of the vertical profile at high beam intensity and the reduction of this broadening when the bare tunes are increased suggests that the cause could be a resonance associated with $\nu_y = 2.0$. It has been pointed out by Baartman [9] that the coherent tunes determine resonant behavior in intense beams, and because of the space charge tune shifts, the coherent tune in the high intensity case will be close to 2.0.

3 ANALYSIS

For the case of 2.07×10^{13} protons in the intensity scan, the profile evolution of the rms vertical emittance closely tracks that obtained without space charge, but for the case of 4.14×10^{13} protons it broadens noticeably after about 700 turns. At this time, a significant fracton of the particles in the highest intensity case have incoherent vertical tunes of 2.0 or less. However, for the case with 2.07×10^{13} protons, the tunes remain above 2. The evoluton of the rms vertical emittances for the high-intensity default tune and increased tune cases shows that the case with raised tunes undergoes less vertical profile broadening than does the default tune case. Calculation of the incoherent tunes also shows that fewer beam particles have tunes below 2.0 for the raised tune case than for the default tune case. Further insight can be gained by an analysis of the longitudinal evolution of the beam.

The injection scheme produces longitudinal beam profiles that are very peaked about the beam center. Because of this, space charge effects are strong and the incoherent tunes highly shifted in this region. For the high-intensity case, the tunes of the particles in the center of the bunch fall squarely about the value 2.0. For the lower-intensity cases, the incoherent tunes are also dependent upon the longitudinal position, but they remain above 2.0. Accordingly, the final vertical positions of the beam particles as functions of the longitudinal coordinate show a significant spread in the center of the bunch for the high intensity case, but this bulge is smaller in the raised tune case and less yet in the lower-intensity cases. This suggests another method of decreasing beam broadening at high intensity: Reduce the peaking of the longitudinal particle density by including a second harmonic in the RF focusing. Adding second harmonic RF focusing at –0.5 times the amplitude of the first harmonic, lowers the peak of the longitudinal density profile and leads to smaller tune depression. When this second harmonic RF focusing is combined with raised bare tunes, calculation shows that the vertical rms emittance evolution follows that of the case without space charge. The incoherent vertical tunes remain above 2.0 even in the bunch center. There is almost no spreading due to space charge. Thus, by decreasing the maximum beam density and by raising the bare tunes, calculations indicate that it is possible to prevent the spreading of the high-intensity beam.

Because space charge forces are involved in the beam broadening, we now examine the envelope oscillations of the beam. Figure 1 plots the vertical second moment oscillations $< y^2 >$ for one turn at the conclusion of the cases examined here. For the case with no space charge, the second moment is constant, but in all other cases there are varying degrees of oscillation. Furthermore, the relative size of these oscillations correlates closely with the degree of beam broadening of the corresponding cases.

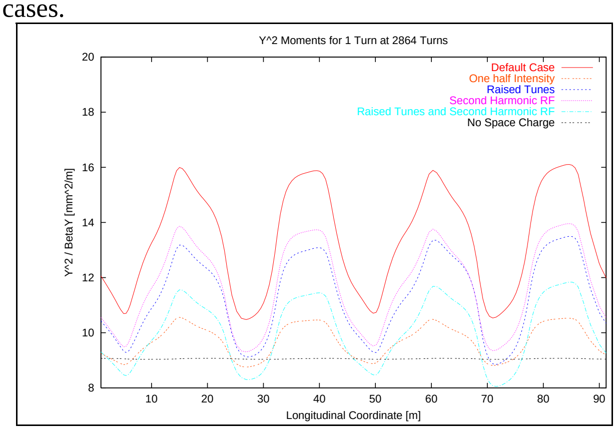

Figure 1. Vertical second moment oscillations of final beam for one turn in the cases presented here.

The envelope curves in Fig. 1 appear to undergo precisely four oscillations per turn. Figure 2 displays the Fourier transformed spectrum of the envelope oscillations for the high intensity default case. The horizontal scale is in units of oscillations/turn with points taken at frequency intervals of 0.02. The frequency component at 4.00 dominates the spectrum. The vertical beam envelope function is in resonance with the lattice at four oscillations/turn. Because the PSR lattice contains 10 superperiods/turn, this resonance involves 2 envelope oscillations per 5 superperiods.

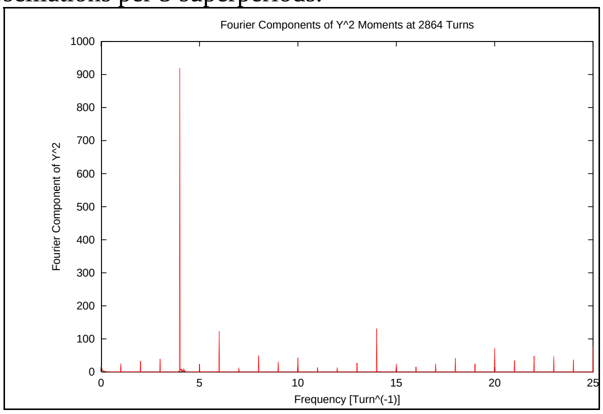

Figure 2. Spectral content of vertical second moment oscillations for the high intensity default case.

To further display the correlation between this envelope-lattice resonance and beam broadening, Fig. 3 plots the vertical rms emittance versus the amplitude of the n = 4 Fourier component of vertical second moment oscillations for the cases presented here. Above a threshold value of about 550, the emittance increases linearly with the size of the n = 4 Fourier component of $< y^2 >$.

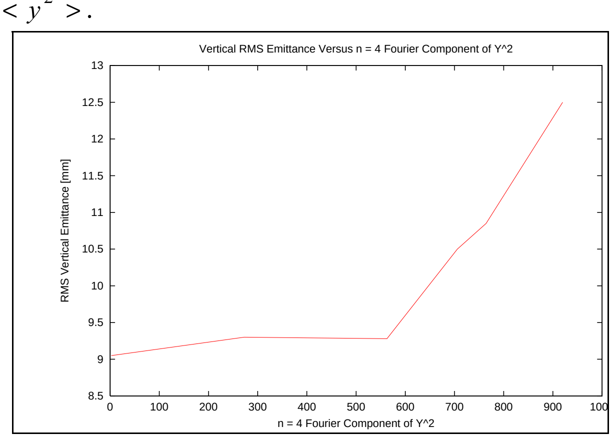

Figure 3. Vertical rms emittance versus amplitude of n = 4 Fourier component of second moment oscillations.

4 CONCLUSIONS

We have compared experimenal profile measurements with numerical simulations of high-intensity proton beams taken after extraction from PSR. The simulations include a careful rendering of the actual injection, accumulation, and extraction scenarios, lattice, and RF focusing scheme. Agreement between the measured and calculated results is reasonably good, but when space charge forces are omitted the vertical profiles differ significantly. Both experimental and calculated results show significant vertical beam broadening at high intensities. Because this occurs with no other changes in the injection scenario, the broadening is a nonlinear process. Analysis shows that the broadening is directly correlated with the size of envelope oscillations in $< y^2 >$ at exactly 4 oscillations per turn. Raising the bare tunes reduces the profile broadening. With single harmonic RF focusing the longitudinal beam distribution becomes quite peaked, which causes the space charge density, the tune shift, and the transverse beam broadening to be strongest at the bunch center. This can be reduced and the transverse beam broadening can be eliminated by including second harmonic RF focusing and raising the bare tunes in the simulations. These results suggest that high-intensity beams can be well contained in accumulator rings through a proper choice of operating tunes, injection scheme, and RF focusing.

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