Observation of Space-Charge Effects in the Los Alamos Proton Storage Ring*

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Abstract

In recent operation of the Los Alamos Proton Storage Ring (PSR), the vertical and horizontal tunes have been moved closer to the integers ($\nu_y = 2.12$, $\nu_x = 3.17$) to enlarge the low-loss working region. In this region, the beam can be significantly affected by space charge. The first observed effects are a nondestructive distortion of the beam profile and vertical growth of beam size sufficient to keep the shifted tunes from crossing the integer, but without large beam loss. At higher intensities, or with tunes closer to the integer, beam blow-up, accompanied by beam losses, can occur. In this paper, we report recent observations of this intensity-dependent effect and discuss implications for future PSR operation.

I. INTRODUCTION

The Los Alamos Proton Storage Ring (PSR) is a fast-cycling storage ring designed to accumulate beam over a macropulse of the LAMPF linac (~1 ms) by multiturn injection through a stripper foil, and compress that beam into a short, single-turn extracted pulse (0.25 μs), that drives a spallation neutron source. The design intensity is 100-μA on target with a 12-Hz repetition rate, which implies $N = 5.2 \times 10^{13}$ protons/pulse. Currently, the PSR achieves 80 μA at 20 Hz ($N = 2.5 \times 10^{13}$), and is limited by beam losses, as well as an instability.[1] Other key PSR parameters include proton kinetic energy ($T = 797$ MeV) with kinetic factors ($\beta, \gamma = 0.842, 1.85$); ring circumference ($C = 2\pi R = 90.1$m); mean beam-pipe radius ($r = 0.05$m); revolution frequency ($f = 2.795$MHz); and a single-bunch harmonic ($h = 1, V = 10$ kV) rf system.

In recent operation, the horizontal and vertical tunes have been moved closer to the integer ($\nu_x = 3.17$, $\nu_y = 2.12$) to obtain more stable operation within a larger low-loss working region. The closer proximity to the integer enhances space-charge effects, and in this paper we report some observations of these effects.

II. SPACE-CHARGE TUNE SHIFTS

The PSR is a high-intensity, low-energy ring, and therefore is expected to have relatively large space-charge effects. Following previous analyses, we expect space-charge forces, as well as tune shifts and spreads from electromagnetic self-fields and from electric and magnetic image forces. At PSR parameters, the largest tune shift is due to the electromagnetic self-field and is given by

$$\Delta\nu_y = -\frac{r_p R \overline{\beta}_y}{2\beta^2\gamma^3 \sigma_y(\sigma_x + \sigma_y)} \frac{dN}{dz} , \qquad (1)$$

where $r_p = 1.536 \times 10^{-18}$ m, (σ_x, σ_y) are the rms beam width and height, $\overline{\beta}_y \cong R/\nu_y$ is an averaged betatron function, and dN/dz is the longitudinal density. $\Delta\nu_x$ is obtained from the same formula with x and y exchanged. The formula assumes Gaussian density profiles and should be modified by a shape factor F for different distributions. The tune shifts apply to small-amplitude motion; larger-amplitude particles have smaller tune shifts, and the $\Delta\nu_{x,y}$ represent maximal "incoherent" tune spreads for the entire beam.

There are also electric- and magnetic-image-field tune shifts, which include both coherent and incoherent effects (see references 2,3,4). At PSR parameters, the image terms are almost an order of magnitude smaller than the direct terms [Eq. (1)] and will not be explicitly discussed here.

The size parameters σ_x, σ_y are given in terms of emittances and betatron function by

$$\sigma_y = \sqrt{\frac{\epsilon_y \overline{\beta}_y}{4\pi}} , \qquad (2)$$
$$\sigma_x = \sqrt{\frac{\epsilon_x \overline{\beta}_x}{4\pi} + \left(\overline{\eta}\frac{\Delta p}{p}\right)^2} ,$$

where the betatron and dispersion functions ($\overline{\beta}_x$, $\overline{\beta}_y$, $\overline{\eta}$) are averaged around the ring and $(\Delta p/p)$ is the rms momentum spread.

The averaging and other approximations introduce several possible inaccuracies in applying the tune-shift formulae to the PSR. The momentum and amplitude distributions are not Gaussian. Neutralization of the beam by stray electrons may occur and would reduce the tune shift. And the dependence on longitudinal density dN/dz can vary substantially. In the calculations below, we have assumed that the longitudinal density profile is a Gaussian distribution with standard deviation approximately equal to the ring radius, so the maximum density is given by

$$\left.\frac{dN}{dz}\right|_{\max} = \frac{N}{\sqrt{2\pi}R} , \qquad (3)$$

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which implies a bunching factor of 2.5. The density profiles were not measured directly in this case and could be somewhat different. However, consistent treatment of similar cases will allow accurate exploration of the changes in the beam.

At typical PSR parameters ($N = 2 \times 10^{13}$, $\Delta p/p = 0.0025$, $\epsilon_x = \epsilon_y = 25\pi$ mm-mR, where $\epsilon \sim 4\sigma^2/\beta^*$), Eq. (1) obtains $\Delta\nu_x = 0.07$, and $\Delta\nu_y = 0.10$, comparable to the distance-to-integer tune shift. The measurements below explore the effects of this proximity.

III. MEASUREMENTS OF EFFECTS ON BEAM

The space-charge effects are greatly dependent on beam size, and in usual operation the beam is injected off-center vertically. This leads to an enlarged beam with a non-Gaussian density and reduced $\Delta\nu_y$. It was noticed that when injected on-axis the beam had a final vertical size that was dependent on beam current. Subsequent experiments and calculations showed that this was a space-charge effect.

In the experiments, a constant total injection width of 625 μs was used with a chopped micropulse width of 250 ns, centered within the 360-ns ring circumference. Intensity was varied by changing the "countdown," (CD) which sets the fraction of linac buckets that contain beam. (CDs of 1, 2, and 4 imply full, half, and one-fourth intensities, respectively.) In this experiment, full intensity was $N \cong 2.3 \times 10^{13}$ protons, although calibration was not precise. The horizontal tune was fixed at $\nu_x = 3.155$, while the vertical tune was varied to test dependences. The beam was extracted immediately at the end of injection, and beam profiles were measured by wire scans in the extraction lines. The results of one vertical and two horizontal wire scans at extraction are used, in conjunction with the TRANSPORT betatron functions at the wire scanner locations, to obtain values of $\Delta p/p$, ϵ_x, and ϵ_y, using Eq. (2). Figure 1 displays vertical wire-scan data at $\nu_y = 2.100$ for countdowns of 4, 2, 1 and shows beam-size increases with intensity. The direct tune shifts were calculated using Eq. (1); image terms were not included but would move the vertical tunes a bit closer to the integer (by $\sim 0.01 - 0.03$) and horizontal tunes farther away.

Complete data for $\nu_y = 2.193$, 2.142, 2.100, and 2.059 are displayed in Table I. Beam-size increase with intensity is shown, particularly for tunes near the integer. For $\nu_y =$ 2.142, 2.100, and 2.059, the beam size increases until the tune shift saturates at values such that $\nu_y - |\Delta\nu|$ remains above the integer.

The beam blow-up is not accompanied by losses until the beam becomes too large (at $\nu_y = 2.100$, CD = 1, and at $\nu_y = 2.059$, CD ≤ 2). Also, significant horizontal beam-size increase occurs only in extreme cases ($\nu_y = 2.142$, 2.100 at CD = 1) with large coupling or large losses.

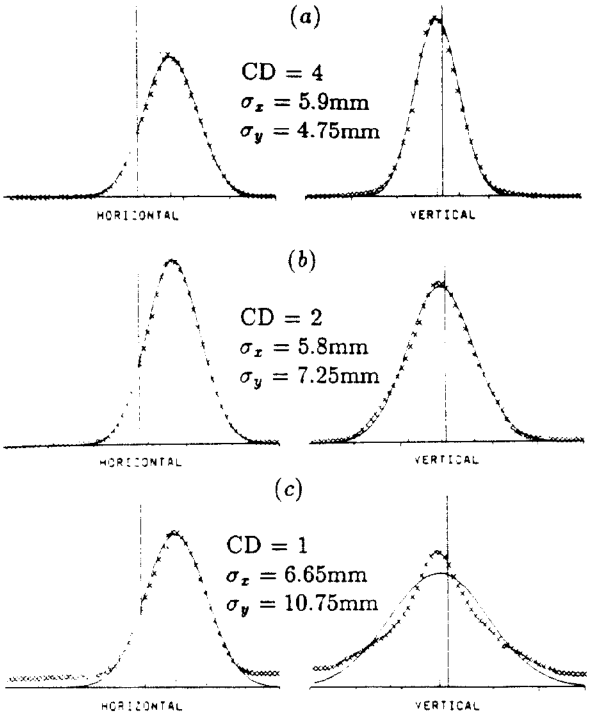

Figure 1. Beam profiles measured by wire scans for (a) Countdown = 4, (b) Countdown = 2, and (c) Countdown = 1.

Table I. Complete Data for ν_y.

	Count-	N	$2\sigma_y$	$2\Delta p/p$	ϵ_x	ϵ_y	$\Delta\nu_x$	$\Delta\nu_y$
ν_y	down	(10^{13})	(mm)	(%)	(mm-mR)		(calculated)	
2.193	4	0.6	8.5	0.38	20.1	8.6	0.035	0.075
	2	1.18	9.9	0.41	22.4	11.6	0.055	0.115
	1	2.3	13.3	0.38	26.6	20.0	0.090	0.148
2.142	4	0.6	8.4	0.41	19.7	8.4	0.032	0.075
	2	1.18	11.5	0.45	16.7	15.7	0.056	0.095
	1	2.3	15.5	0.41	25.4	28.6	0.082	0.113
2.100	4	0.6	9.5	0.47	15.5	10.7	0.031	0.061
	2	1.18	14.5	0.45	16.4	25.0	0.050	0.068
	1	2.3	21.5	0.31	44.0	55.0	0.055	0.064
2.059	4	0.6	12.6	0.46	15.0	18.9	0.028	0.043
	2	1.18	20.6	0.45	16.0	50.5	0.041	0.039
	1	beam loss prevented operation						

In the calculation, we used $\overline{\beta}_x = 4.6m$, $\overline{\beta}_y = 6.8$, $\overline{\eta} = 1.8m$ and $B = 2.507$.

IV. OPERATIONAL OBSERVATIONS

In usual operation the beam is injected off-axis vertically, so that the beam fills the aperture. This minimizes $\Delta\nu_{x,y}$. The injected beam is far from Gaussian and is actually relatively "hollow" vertically. Figure 2 shows vertical beam profiles at extraction from production conditions ($N \cong 2.25 \times 10^{13}$ at a CD of 1). Figure 2 shows profiles at CDs of 4, 2, 1 (1/4, 1/2, and full intensity). At lower intensities, the beam has a pronounced "hollow" shape vertically with an intensity minimum at $y = 0$. With higher intensity, the distribution changes becoming smoother, with a flat density near $y = 0$. This change reduces the space-charge tune spread. Beam losses are not greatly increased by the distribution shifts; in changing from CD = 2 to CD = 1, loss-monitor readings increased from 24 to 52 μV-s, only slightly more than linear with current.

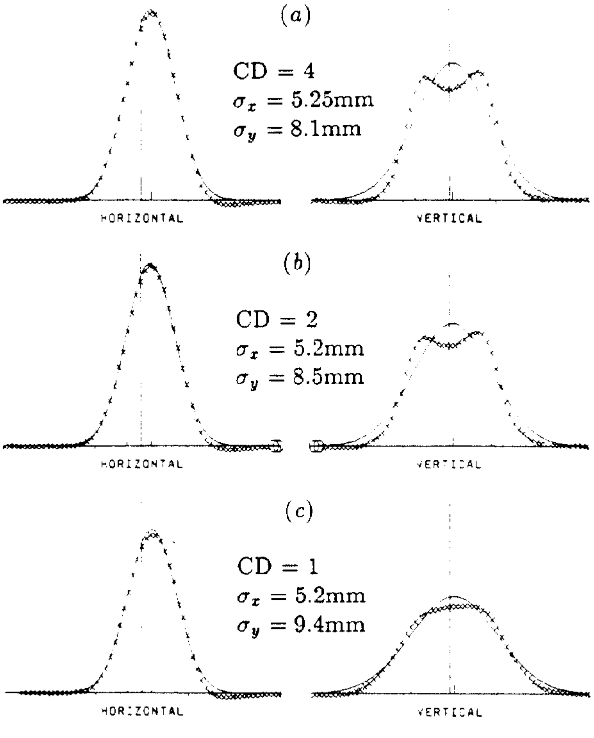

Figure 2. Beam profiles measured by wire scans for (a) Countdown = 4, (b) Countdown = 2, and (c) Countdown = 1. The beam was injected off-axis vertically.

At these parameters ($N = 2.25 \times 10^{13}$, $\epsilon_x \cong 17\pi$mm-mR, $\Delta p/p \cong 0.0018$, $\epsilon_y \cong 42\pi$, $B = 2.507$) and Gaussian formulae, we obtain $\Delta\nu_x = 0.092$, and $\Delta\nu_y = 0.089$. Because $\nu_x = 3.17$ and $\nu_y = 2.12$, the shifted vertical tune is close to the integer. At CD = 1, the proximity to the integer has been reduced by the flattening of the distribution, but without much increase in beam loss.

V. SUMMARY AND DISCUSSION

Under both production and development conditions, space-charge effects on the PSR beam have been observed. The first effect is a nondestructive distortion of the vertical beam profile and/or a size increase sufficient to keep shifted tunes from crossing the integer, but without large beam losses. At higher intensities, or ν_y nearer the integer, beam blow-up with losses occurs. This general behavior should also occur in other high-intensity synchrotrons with large, direct space-charge forces (e.g., BNL AGS and Booster, Fermilab Booster, CERN PS and Booster, SSC Low-Energy Booster) and should be considered in their design and operation. We note that in some of these cases (unlike the PSR), nondestructive emittance increase is undesirable. Our observations apply to situations in which the tunes are in proximity to an integer resonance and not to other resonances. When the tunes are in proximity to other resonances (N/3, N/2) the results could be somewhat different and should be explored.

Current operational parameters ($\nu_x \cong 2.17$, $\nu_y \cong 2.12$) are close to vertical space-charge limits. Significant increases in intensity (from $N \cong 2.5 \times 10^{13}$) will require increasing the vertical tunes.

VI. REFERENCES

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