OBSERVATION OF THE TUNE DEPENDENCE OF THE STABILITY THRESHOLD CURRENT IN THE PSR*

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Abstract

In the high-intensity unbunched-beam experiments carried out in the Proton Storage Ring at Los Alamos National Laboratory, the threshold current of vertical transverse instability showed pronounced differences when the betatron tune varied across an integer. In this paper, we shall present our experimental observations and discuss the possible relations between the threshold current and the machine impedance. The possible effects related to the distorted closed orbit are also discussed.

Introduction

The Proton Storage Ring (PSR) now in operation at Los Alamos is a high-current accumulator designed to deliver intense 800-MeV proton pulses for driving the Los Alamos Neutron Scattering Center (LANSCE) spallation source. The ring compresses up to 1000-μs-long macropulses from the LAMPF linear accelerator into 250-ns bunches and ejects them to a neutron production target, providing an output optimized for the thermal-neutron-scattering research. The design pulse rate and peak pulse intensity of the PSR are 12 Hz and 5.2×10^{13} protons per pulse (ppp), yielding a 100-μA average current when full performance is reached. At present, the PSR is operated in production at average currents up to 35 μA. High current production has been inhibited by beam losses during accumulation.

Figure 1 shows the equipment layout of the storage ring and the associated beamlines. A summary of important parameters is given in Table I. More information on the PSR and its operation is available in other publications.[1,2]

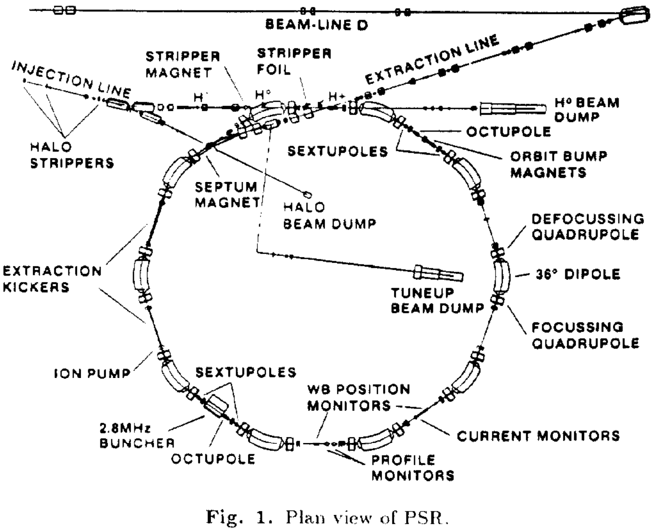

Fig. 1. Plan view of PSR.

Coherent instabilities have been observed in the PSR when the beam intensity is higher than the 5×10^{12} ppp level. By suitable parameter adjustment, the maximal stable beam intensity has reached 4×10^{13}. The observed collective instability was identified as a transverse type. We found that the threshold currents exhibit pronounced differences when the vertical betatron tune ν_y is varied across the integers 2 and 3.[3]

TABLE I. PSR Parameters

STORED BEAM

Bunch length	270 ns (250 ns)
Protons/bunch	$5.2 \cdot 10^{13}$ $(3.4 \cdot 10^{13})$
Pulse rate	12-24 Hz (12 Hz)
Beam ion, energy	H^-, 797 MeV
Beta, gamma	0.842, 1.849
Emittance (mm·mrad)	
Extracted (horiz)	7 mm·mrad
Extracted (vert)	20 mm·mrad
$\delta p/p$ (full width)	
Injected	±0.001
Extracted	±0.003
Peak current	46.3 A (30.0 A)
Average current	100 μA (30 μA)

RF and INJECTION

Buncher harmonic	1
Buncher frequency	2.795 MHz
RF amplitude (max)	15 kV
Synchrotron tune	0.0006
Filling time	750 *mus* (975 μs)

LATTICE

Orbit circumference	90.2 m
Focusing structure	FODO, 10-cell
Acceptance (x,y)	124, 167 mm×mrad
Aperture(β_{mx})	9.72 cm
Transition gamma	3.08 (3.22)
Betatron tune (x,y)	3.23, 2.21
Phase advance/cell	113°(x), 79°(y)
Betatron amplitude	
horiz(min, max)	2.0 m, 14.1 m
vert (min, max)	2.0 m, 14.2 m
Dispersion (min, max)	1.1 m, 2.2 m
X-chromaticity	−0.82 (−1.25)
Y-chromaticity	−1.30 (−0.96)

Experimental Observations

The first threshold current versus tune experiment was carried out in late 1987 followed by a second experiment within a month. The third experiment was performed in 1988, about one year after the first experiment. In each run, the vertical tune at zero intensity was set first, then the beam current was increased from below the instability threshold until a marginal instability was observed. The beam current, monitored by a toroidal current monitor, was recorded and the same procedure was repeated for different vertical tunes. The horizontal tune was kept almost constant ($3.22 \leq \nu_x \leq 3.26$) and the bunching RF field was off in all three experiments. The experimental data indicate a growth of vertical oscillations when instability occurs. The highest stable beam current is shown in Fig. 2 as a function of the vertical tune. The data from the two earlier experiments show that the maximal stable circulating currents are below 2 A at nominal operation ($\nu_y = 2.23$). As ν_y is decreased toward 2.0, the threshold currents increase and approach a maximum around 3.5 A. When ν_y is moved slightly below 2.0, the currents drop to less than 2 A in most cases. As ν_y is further decreased, the current increases again. For $\nu_y \approx 3$, the latest experimental data show threshold currents of 2 A at $\nu_y = 2.9$ and 3 A at

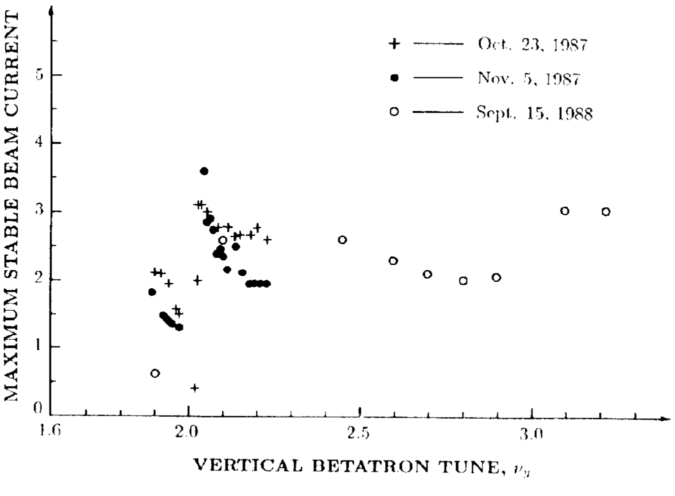

Fig. 2. The unbunched beam stability threshold current as a function of the vertical tune.

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$\nu_y = 3.1$, which indicate that a discontinuity of the threshold current also occurs at $\nu_y = 3$. Note that for the same separation of the tune from an integer, the threshold currents near $\nu_y = 3$ are higher than these at $\nu_y = 2$.

Observations on the bunched beam case indicate similar threshold current dependences on the vertical tune.

Some Speculations

The behavior of the maximal stable current shown here has not been well understood for several reasons: (1) this kind of threshold current behavior is not explicitly described in the existing theory; (2) the details of the machine impedance are unknown; (3) we have not seen any other accelerator laboratory reporting the same kind of observation; and (4) we were limited by machine time available for these experiments. We still lack some auxiliary data, such as the signal spectra at low frequencies and energy spread, etc., which might provide sufficient information for deciphering the observed phenomenon.

In this paper, we shall discuss two mechanisms that may be relevant to the observed behavior of the stability threshold current: (1) the resistive-wall and space-charge effects and (2) the effects of the distorted closed orbit and the asymmetric transverse impedance.

(1) Resistive-Wall and Space-Charge Effects

A frequently used criterion for coasting beam transverse stability[4] shows that the threshold current is related to the transverse impedance $Z_\perp$ by

$$I_{th} = \frac{4Fm_oc^2\gamma\beta_\perp|(n-\nu_y)\eta - \nu_y\xi|}{q\bar{\beta}|Z_{\perp n}|}\left(\frac{\delta p}{p}\right) \ , \qquad (1)$$

where n is the azimuthal harmonic number of the perturbed charge density, $\bar{\beta}_\perp$ is the averaged beta-function value, F is the form factor, $\delta p/p$ is the half-width of the momentum spread among protons, and the other symbols are defined according to usual conventions. A well-known component of the impedance is the resistive-wall impedance $Z_{\perp n}^{rw}$ that is related to the harmonic number n by

$$Z_{\perp n}^{rw} = \frac{2\pi RZ_o}{b^3\sqrt{2\sigma\mu_o}} \frac{\sqrt{|n-\nu_y|\Omega_o}}{(n-\nu_y)\Omega_o} \propto \frac{1}{\sqrt{|n-\nu_y|}} \ , \qquad (2)$$

where R is the radius of the ring, $Z_o = 377\Omega$, μ_o is the permeability of free space, Ω_o is the angular frequency of revolution of the "on momentum" beam particles; b and σ are the radius and the conductivity of the surrounding beam pipe, respectively.

It was shown in Ref. 5 that the n^{th} mode is stable for $n < \nu_y$ and unstable for $n > \nu_y$ because the sign of the resistive-wall impedance depends on the sign of $n - \nu_y$. Equation (2) shows that the resistive-wall impedance rises sharply when the tune approaches an integer. Under normal operating conditions, we believe that the instability is dominated by relatively high harmonics ($n \gg \nu_y$). However, for the $\nu_y \approx 2$ and $\nu_y \approx 3$ regions, one may expect that the resistive-wall impedance should dominate the impedance seen by the $n = 2$ and $n = 3$ modes, respectively. One can obtain from Eqs. (1) and (2) that

$$I_{th} \propto \sqrt{n - \nu_y} \ . \qquad (3)$$

For the tune not too far below the integer 2, the trend of the threshold current described by Eq. (3) is in fair agreement with the fast drop of the experimental threshold current shown in Fig. 2. For $\nu_y \approx 2$ and $\nu_y > 2$, many of the $n \geq 3$ modes could be unstable; according to Eq. (2), the $n = 3$ mode should see the highest resistive-wall impedance among unstable modes. Note that for $2 \leq \nu_y < 3$, $Z_{\perp 3}^{rw}$ has a minimum at $\nu_y = 2$. Also note that for the PSR, $\eta = 0.19$, and $\xi = -1.0$; therefore, Eq. (1) indicates that the $\nu_y\xi$ term dominates in the lower harmonics.

In the imaginary part of the impedance, a familiar component arises from the space-charge effect that depends on the beam radius a as

$$Z_\perp^{sc} = \frac{RZ_o}{\beta^2\gamma^2}\left(\frac{1}{a^2} - \frac{1}{b^2}\right) \ , \qquad (4)$$

which indicates that the space-charge impedance decreases as the beam radius increases. Experiments in the PSR have observed that the instability threshold increases when the vertical beam size is increased by mismatched injection at the usual operating point ($\nu_y = 2.23$). We speculate that the beneficial effect of larger beam size may also be obtainable through enhanced error effects near an integer tune, for example, through the gradient defects in the focusing magnets.

The above theoretical discussions encourage the following hypothesis: When $\nu_y < n$ ($n = 2$ or 3), the n^{th} mode is the most unstable resistive-wall mode; also when $\nu_y > n$, the $(n+1)^{th}$ mode is the most unstable mode. The threshold current in the $\nu_y < n$ and $\nu_y > n$ regions may be mainly determined by the threshold currents of modes n and $n + 1$, respectively, even though there is a possibility that the threshold current is determined by some higher harmonic mode or other effects. The discontinuity of the threshold current is caused by the minimal impedance seen by mode $n+1$ and the maximal impedance seen by mode n at $\nu_y = n$. An example of the hypothetical situation has been proposed in Ref. 3 to explain the observation for $\nu_y \approx 2$.

The above hypotheses suggest that we should examine the vertical signal and the transverse impedance in the low-frequency region from several kilohertz to a few megahertz. In one set of observations, low-frequency vertical oscillations near $|n - \nu_y|\Omega_o$ were observed when there was an instability and the vertical tune was just before the integer. These observations should be confirmed and studied quantitatively. Because the chromaticity term dominates the stability threshold current in the lower harmonics, as stated before, we should probably look for the chromaticity dependence of the threshold current, too. It is also suggested that the transverse beam dimension be monitored when the same experiment is repeated in the future.

(2) Closed-Orbit Distortion-Related Effects

When ν_y is near an integer, the parametric resonance effect that causes instability to the single-particle orbit can also enhance the distortion of the closed orbit. The distorted closed orbit may behave quite differently when ν_y is just below or just above an integer.

Let us assume the closed-orbit distortion is due to some kind of perturbing force (e.g., from magnet alignment errors) that can be expressed in terms of the azimuthal harmonics around the ring by $\sum_n \epsilon_n \cos(n\theta)$, where θ is the azimuthal angle around the ring and ϵ_n is the nth harmonic of the acceleration caused by the perturbing force. Then for $\nu_y \approx n$, the displacement for a single particle can be shown, in the smooth approximation, to be

$$y = h\cos(\nu_y\theta + \psi) + \frac{\epsilon_n}{2n(\nu_y - n)}\cos(2\theta) \ , \qquad (5)$$

where h and ψ depend on the initial conditions. The first and second terms on the right-hand side of Eq. (5) represent the betatron oscillation relative to the closed orbit and the distortion in the closed orbit, respectively. Therefore, at the same location in the ring, the distortion of the closed orbit can have the same magnitude but a different sign depending on whether ν_y is above or below an integer. This phenomenon is seen in the PSR. Figure 3 shows the closed orbits above and below the integer tune of 3.

If the transverse impedance is asymmetric with respect to the horizontal plane and is not uniformly distributed around the ring, then the impedance experienced by the beam and, hence, the stability threshold current depend on the tune. The possible sources of asymmetric impedance in the PSR may come from the following asymmetric structures: (1) 19 ion-pump ports, each

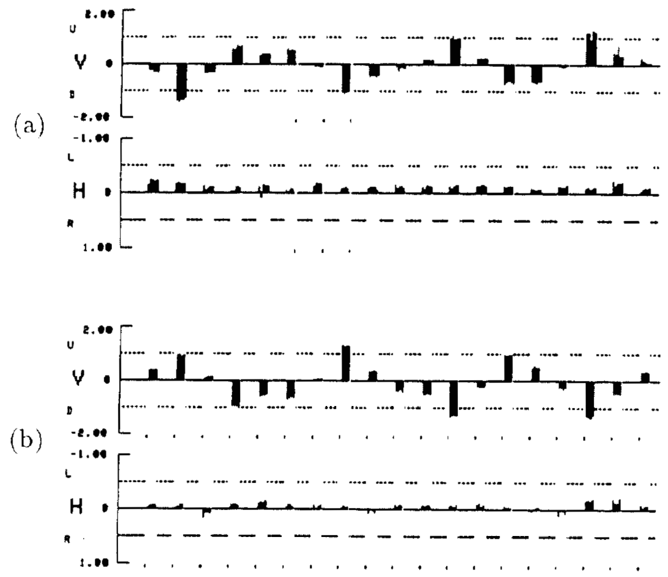

Fig. 3. Closed orbits in the PSR for (a) $\nu_y = 3.1$, and (b) $\nu_y = 2.9$. The figure shows the deviations of the closed orbit from the design orbit at ninteen locations around the ring. The deviations are shown as vertical bars in unit of centimetre. Each vertical bar contains five most updated samples.

having about 2 in. of indentation on the top side of the beam pipe; (2) the stripper foil box; (3) two- or three-harp beam-profile scanner boxes that are tilted at 45° from the horizontal plane; and (4) several tilts on the beam pipe with a slope less than or equal to 6.25×10^{-4}.

However, a cursory analysis on this aspect has shown that this kind of effect, by itself, should be too weak to cause any sizable discontinuity in the threshold current as we have observed in the PSR.

Conclusions

The behavior of the threshold current for vertical tune near the integers 2 and 3 could be related to the resistive-wall-type instability of modes $n = 2$ to 4 together with the space-charge effect. It is conjectured that the closed-orbit distortion and a nonuniformly distributed asymmetric transverse impedance may contribute to some degree to the discontinuity of the threshold current when the vertical tune crosses an integer.

For a better understanding of the observed phenomenon, we believe that more experimental data are needed. We must be able to measure the coherent signal from the beam for frequencies less than 10 MHz to check the $n = 2$ to 4 modes. It is also suggested that the same experiment be repeated with chromaticity and closed-orbit manipulations.

Another interesting experiment would be to vary ν_x across the integer 3 to see if a similar instability threshold pattern appears. The instability is usually associated with vertical motion; however, for $\nu_x \leq 3$ a horizontal instability may appear, with behavior similar to the vertical resistive-wall instability.

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