Increasing Threshold Beam Current by Bunch Filling Pattern*

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Abstract

To cure the coupled bunch mode instabilities (CBMI's) in the PLS storage ring, we have studied various bunch filling patterns which generate Landau damping by bunch-to-bunch synchrotron frequency spreads at a low filling ratio. By this Landau damping, we can increase the stored beam current further without any harmful CBMI's. We have also obtained the small and stable beam by changing the filling pattern. In this paper, we have described the way how to determine the filling pattern which generates Landau damping, and the relation between various filling patterns and longitudinal CBMI's.

1 INTRODUCTION

The most harmful HOM in the PLS RF cavities is the TM_{020} mode (1301.1 MHz). To avoid the CBMI invoked by the mode, an active longitudinal feedback system using programmable digital signal processors (DSPs) was installed in the PLS storage ring during the summer maintenance period in 1999. During the LFS commissioning, we have obtained various useful bunch-to-bunch diagnostic information [1]. The bunch filling patterns generate bunch-to-bunch frequency spreads and hence produce Landau damping. The bunch-to-bunch frequency spreads break the coupling between circulating bunches, and reduce the amplitudes of the CBMI's.

2 CBMI AND LANDAU DAMPING

2.1 Decoupling CBMI by Landau damping

The coupled bunch mode instabilities are characterized by a definite oscillating phase difference between equally spaced adjacent coupled bunches, which is given by

$$\Delta\phi = \frac{2\pi n}{M}\,, \qquad (1)$$

where M is the total bunch number, and n is the coupled bunch mode number $(1 \sim M-1)$. It is possible to decouple the coupled bunch modes or to break this definite phase difference between coupled bunches by generating synchrotron frequency spreads in every bunches. This synchrotron frequency spread is mainly produced by the non-linear sinusoidal RF cavity voltages. The finite phase difference between the adjacent coupled bunches given by Eq. (1) is broken by the synchrotron frequency spreads. Therefore, the CBMI's can be simultaneously damped at the rate of the amplitude-dependent synchrotron frequency spread, which is known as Landau damping.

There are two well known ways of increasing the synchrotron frequency spread in order to generate Landau damping and increase threshold beam currents: (1) the intra-bunch spread between particles within each bunch by Landau cavity (2) the inter-bunch spread between bunches by fractional filling. In this experiment, we generated Landau damping by filling bunches fractionally, since the empty bucket gaps in bunch trains induce the non-linear RF voltage modulation due to a strong beam loading [2].

2.2 Filling patterns for Landau damping

To generate Landau damping, we should determine the filling patterns which can generate large synchrotron frequency spreads. There is a finite stable region of the impedance where the collective motion can be Landau damped. The stable region can be extended by increasing the number of empty buckets [3], and the damping of all possible CBMI's is only possible when the synchrotron frequencies of individual bunches are different [4]. We define the filling ratio F as $N_t/(N_t + N_{tg})$ where N_t is the number of filled buckets in a bunch train and N_{tg} is the number of empty buckets in the same bunch train. For a sinusoidal RF voltage modulation even in the case where the period of the modulation is one revolution, there are pairs of bunches which have the same synchrotron frequency. In this case, decoupling of the CBMI's can be obtained by filling only buckets that are located in the linear range of the RF modulation which means that F is less than 0.5 [4]. Furthermore, when F is less than 0.4, the synchrotron frequency spread is large enough to generate an effective and strong Landau damping for all CBMI's [2]. For $N_t > 5$, and F is less than 0.5, the Landau damping rate with a constant frequency spread can be given by

$$\frac{1}{\tau_L} = \frac{\pi \cdot \Delta f_s}{[0.577 + \ln(N_t - 1)]}\,, \qquad (2)$$

where τ_L is the Landau damping time and Δf_s is the synchrotron frequency spread [4]. The Landau damping rate can be increased by reducing the filling ratio F with a given frequency spread [5]. Since the phase shift due to the beam loading depends on the beam current and the number of empty buckets N_{tg}, a higher frequency spread can be obtained by increasing the beam current and the number of empty buckets [2], [6]. However, if we increase the phase shift too much by the large number of empty buckets, the photon beam quality at the end of users' beamline will fluctuate due to the too strong modulated synchrotron oscillation and the transverse CBMI's which are generated when

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Table 1: Parameters for four filling patterns.

	one-train	three-train	four-train	six-train
E [GeV]	2.04	2.04	2.04	2.04
N_t	400	30	30	25
N_{tg}	68	126	87	53
N_f	400	90	120	150
I_b [mA]	125.60	168.79	167.23	165.54
I_b/N_f [mA]	0.31	1.88	1.39	1.10
F	0.85	0.19	0.26	0.32
Δf_s [Hz]	2.9	80.7	49.1	31.7
τ_L [msec]	713.69	15.56	25.57	37.71
I_{th} [mA]	148.5	220.9	191.8	177.3
A_s [deg]	7.0	0.6	1.7	3.5
H_s [MHz]	1.07	3.20	4.27	6.41

the beam current per a bunch is high. Therefore, we have to divide a long bunch train into several shorter trains and restrict the phase shift in each bunch train to a finite value. The total phase shift from the first to the last bunch in a bunch train due to the fundamental mode beam loading is given by

$$\Delta\phi_{1,N_t} \approx \frac{2k \cdot I_b}{f_o \cdot N_f \cdot V_c \cdot \cos\phi_s}\left[\frac{(N_t-1)N_{tg}}{(N_t+N_{tg})}\right], \quad (3)$$

where k is the loss factor $(= (\omega_{RF}/2)\cdot(R/Q))$, I_b is the stored beam current, N_f is the number of total filled buckets in a storage ring $(= N_t \times train\,number)$, V_c is the peak cavity voltage, ϕ_s is the synchronous phase for the sine-type RF gap voltage, and the revolution frequency f_o is 1.06855 MHz for the PLS storage ring [6]. Since the loss factor for the fundamental mode is much larger than that of higher order modes in the PLS storage ring, we consider only the fundamental mode beam loading effect in determining filling patterns. There are two conditions that determine the filling patterns; the filling ratio $F \leq 0.4$ to generate an effective and strong Landau damping for all CBMI's and the phase shift between the first and the last bunch $\Delta\phi_{1,N_t} \leq 2°$. The value of $2°$ is that of the phase shift from the first to the last bunch (400th) in the current one-train operation. Among possible filling patterns which satisfy with two conditions simultaneously, the filling patterns used in this experiment are listed in the above part of Table 1 where all filling patterns are tuned to the same RF cavities temperature status.

3 EXPERIMENTAL RESULTS

3.1 Frequency spreads

The synchrotron frequency spreads can be obtained by using the formula of the synchrotron frequency and the standard deviation of the bunch-to-bunch synchrotron phases via the LFS recording function as shown in Figs. 1 and 2 [5]. The unit, deg@RF, means the bunch phase (deg) with respect to a reference oscillator of the LFS. The phases of 30 filled buckets for one-train operation are plotted in Fig. 1

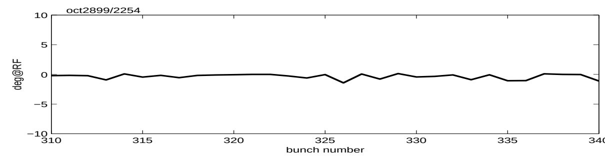

Figure 1: Bunch-to-bunch phases of one-train operation with the filling ration, $F = 0.85$.

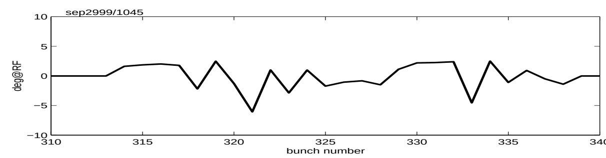

Figure 2: Bunch-to-bunch phases for six-train operation with the filling ratio, $F = 0.32$.

while the phases of 30 buckets (25 filled buckets + 5 empty buckets) with the corresponding bunch number for six-train operation are plotted in Fig. 2. Though two beam currents are similar (125.60 mA for one-train operation and 119.60 mA for six-train operation, respectively), a larger spread in Fig. 2 is generated by the lower filling ratio F. For a given current, the frequency spreads are increased by decreasing the filling ratio F as shown in Fig. 3. Also, for a given filling ratio, the spreads are proportional to the beam current as shown in Fig. 4 which is the result of four-train operation.

3.2 One-train operation

Due to the large filling ratio ($F = 0.85$), the synchrotron frequency spread of this pattern is very small ($\Delta f_s = 2.9$ Hz). Therefore, the Landau damping time, τ_L is 713.69 msec which is obtained by using Eq. (2) and the measured frequency spreads. The growth time τ_G of the most harmful CBMI due to the TM_{020} mode obtained by the LFS grow/damp process [1] is about 11.51 msec at 100 mA, 2.04 GeV and RF cavity temperature tuned status. This growth time is much faster than the Landau damping time of 713.69 msec. Therefore, the synchrotron radiation damping with a damping time $\tau_s = 7.84$ msec at 2.04 GeV can mainly damp the CBMI. Threshold beam current is determined when the net growth time τ_G is balanced with the total damping time τ_D $(1/\tau_D = 1/\tau_s + 1/\tau_L)$ [1], [5]. We found the threshold beam current for the TM_{020}

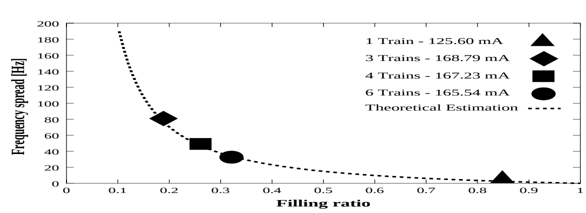

Figure 3: Filling ratio vs. frequency spread Δf_s.

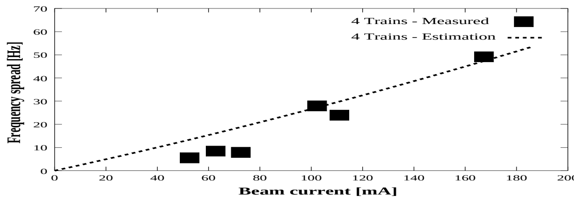

Figure 4: Beam current vs. frequency spread Δf_s for four-train operation with the filling ratio, $F = 0.26$.

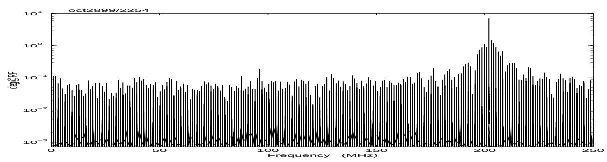

Figure 5: Pseudo-spectrum for one-train operation at the beam current of $I_b = 125.60$ mA.

mode is about 148.5 mA at 2.04 GeV [1]. Though this CBMI exists, we are operating this filling pattern with a beam current of about 170 mA at 2.04 GeV by suppressing its growth rate with the RF cavity temperature control system. During the normal operation, we have occasionally experienced the beam blow-up due to this CBMI. The pseudo-spectrum for this filling pattern is shown in Fig. 5. We can see a high and sharp upper sideband at about 200 MHz which is aliased from the TM_{020} mode. Its maximum spectrum level is about 7.0 deg@RF.

3.3 Multi-train operations for Landau damping

In case of three-train operation, a low filling ratio of $F = 0.19$ and a larger frequency spread of $\Delta f_s = 80.7$ Hz is measured. The large frequency spread generates strong Landau damping with a damping time of $\tau_L = 15.56$ msec. For the TM_{020} mode with $\tau_G = 11.51$ msec at $I_o = 100$ mA and 2.04 GeV, and $\tau_s = 7.84$ msec, the threshold beam current I_{th} for three-train filling pattern is about 220.9 mA which is 72.3 mA higher than that of the one-train operation. Therefore, with Landau damping, we will be enable to damp all CBMI's up to 220.9 mA.

During this experiment, due to the allowed vacuum limitation and the transverse CBMI's in the PLS storage ring, we could not increase the beam current beyond 215.0 mA. Although the beam current is high, $I_b = 200.31$ mA, we can not find any large-amplitude sideband due to the harmful longitudinal CBMI for this filling pattern as shown in Fig. 6. The many sharp peaks with a constant separation are due to the revolution harmonics of three trains whose the separation is given by $(f_{RF}/h) \times n_t = 3f_o \sim 3.2$ MHz where h is the harmonic number and n_t is the train number. Although the beam revolution harmonics are omitted in the pseudo-spectrum, the revolution harmonics of the bunch trains are not omitted. Note that these revolution harmonics have no relation with any harmful CBMI, and all sidebands due to the CBMI's were strongly damped down

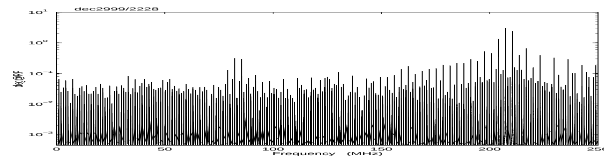

Figure 6: Pseudo-spectrum for three-train operation with the beam current of $I_b = 200.31$ mA.

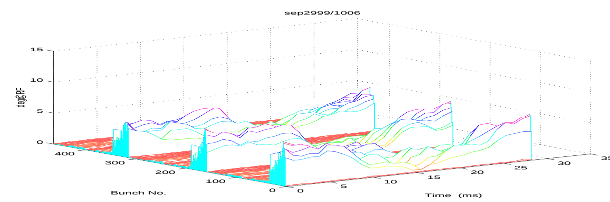

Figure 7: Time domain 90-bunch oscillations of three-train.

to the 0.2 deg@RF level as shown in Fig. 6. After considering the sideband level, we will be enable to increase threshold beam current further when we cure the vacuum limitation and the transverse CBMI's.

Similar decoupled motions with somewhat large amplitudes than that for three-train operation can be obtained in cases of four-train and six-train. Their results are shown in Figs. 3 and 4 and are summarized in the below part of Table 1 where I_{th} is the threshold beam current for TM_{020} mode, A_s is the maximum amplitude of the synchrotron oscillation due to the strongest CBMI, and H_s is the separation between the bunch train revolution harmonics.

4 CONCLUSIONS

Landau damping was generated for three different filling patterns with low filling ratios. Landau damping can be increased by increasing the beam current and by decreasing the filling ratio. The threshold beam current of a CBMI due to the TM_{020} mode can be increased significantly from 148.5 mA by changing the filling pattern only. As a result, we were able to increase the beam current up to 215.0 mA without any harmful CBMI.

5 ACKNOWLEDGMENTS

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