Commissioning Results of PLS Longitudinal Feedback System*

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Abstract

In the Pohang Light Source (PLS), there are serious efforts to increase the stored beam current up to the design value of 400 mA at 2.0 GeV. The main limitation is due to the longitudinal coupled bunch mode instabilities (CBMI's) which are generated by interactions between higher order modes (HOM's) of RF cavities and circulating beams. To cure those CBMI's, a longitudinal feedback system (LFS) using parallel digital signal processors (DSPs) was installed during the summer maintenance period in 1999. Besides the cure of CBMI's, this programmable LFS can be used to obtain various beam diagnostic information by using the recording function of the LFS. At present, we have damped all CBMI's at 237.0 mA, 2.04 GeV by the LFS. The damping time of the LFS is about 2 msec which is much faster than the growth time of the most harmful CBMI.

1 INTRODUCTION

Recently, we have turned on the PLS LFS to cure the CBMI's [1]. All sidebands due to CBMI's have been damped by 70 dB at 237.0 mA, 2.04 GeV, and 38% reduction in the horizontal emittance is obtained. During the LFS commissioning, we have obtained various useful diagnostic information such as HOM frequencies of RF cavities which generate CBMI's, instability growth rates of those CBMI's, the threshold beam current which can be obtained by the LFS, the beam pseudo-spectra that are beam spectra without beam revolution harmonics, the dependence of HOM's on the temperatures of RF cavities, Landau damping by changing the bunch filling patterns [2], comparison of two damping efficiencies between the energy ramping to 2.5 GeV and active LFS at 2.04 GeV, and finally the source of the LFS malfunction at high beam current due to RF noise modulation. In this paper, various commissioning results of the longitudinal feedback system are described.

2 GROWTH RATES OF CBMI'S

According to CBMI theory, CBMI's generate sidebands of the beam spectrum around revolution harmonics in the frequency domain whose frequencies are given by

$$f_{p,n,m} = (p \cdot M + n + m \cdot \nu) \cdot f_o\,,\ -\infty < p < \infty\,, \quad (1)$$

where p is any integer, M is the total bunch number, n is the coupled bunch mode number $(0 \sim M-1)$, m is the azimuthal within bunch modes ($m = 1$ for the dipole mode, $m = 2$ for the quadrupole mode ...), ν is the synchrotron tune ν_s for the longitudinal CBMI's or the betatron tune $\nu_{x,y}$ for the transverse CBMI's, and f_o is the revolution frequency. For a given coupled bunch mode n and all azimuthal within bunch modes m, the total beam current I_b generates an effective longitudinal wakefield voltage V_n which is given by

$$V_n = iI_b\phi_n \sum_{p=-\infty}^{\infty} \sum_{m=1}^{\geq 1} \frac{f_{p,n,m}}{f_{RF}} Z_{||}(f_{p,n,m}) S(f_{p,n,m}), \quad (2)$$

where ϕ_n is the amplitude of synchrotron phase motion for the coupled bunch mode n, and f_{RF} is the RF frequency. $S(f_{p,n,m})$ is the form factor which cuts the summation series. Here, we have ignored the radial within bunch mode number k, and $Z_{||}(f_{p,n,m})$ is the longitudinal complex impedance which is a function of temperatures of RF cavities [3]. For Gaussian bunches, the form factor $S(f_{p,n,m})$ is given by $e^{-(2\pi f_{p,n,m} \cdot \sigma_\tau)^2}$ where σ_τ is the bunch length in time scale. Note that negative values of $f_{p,n,m}$ (or negative value of p) will reverse the sign of effective wakefield voltage, and these are seen as lower sidebands by a spectrum analyzer. Therefore, in the case of above transition, the resistive longitudinal $Z_{||}$ generates longitudinal CBMI's for upper sidebands while a damping is generated due to the negative voltage V_n for lower sidebands. For a given coupled bunch mode number n and all azimuthal within bunch modes m, the total net growth rate $1/\tau_N$ is given by

$$\frac{1}{\tau_N} = \frac{1}{\tau_G} - \frac{1}{\tau_D}\,, \quad (3)$$

$$\frac{1}{\tau_G} = \frac{\alpha f_{RF}}{2\nu_s(E/e)} \frac{Im[V_n]}{\phi_n}\,, \quad (4)$$

$$\frac{1}{\tau_D} = \frac{1}{\tau_s} + \frac{1}{\tau_L} + \frac{1}{\tau_{fb}}\,, \quad (5)$$

$$\frac{1}{\tau_s} = 8.85 \times 10^{-5} \cdot \frac{f_o E_G^3}{\rho}\,, \quad (6)$$

where $1/\tau_G$ is the net growth rate due to the lower and upper sidebands, $1/\tau_D$ is the total damping rate which includes the synchrotron radiation damping rate $1/\tau_s$, the Landau damping rate $1/\tau_L$ due to the bunch-to-bunch synchrotron frequency spreads and the longitudinal feedback damping rate $1/\tau_{fb}$ [1], α is the momentum compaction factor, E (E_G) is the beam energy in eV (GeV), e is an electron charge, and $\rho = 6.306$ m is the bending magnet radius of the PLS storage ring.

Since the longitudinal complex impedance $Z_{||}(f_{p,n,m})$ is a function of the RF cavity temperature, total net growth rates of CBMI's are also a function of the RF cavity temperature from Eqs. (2), (3), and (4) [3]. Since the amplitude of

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the synchrotron oscillation decays exponentially like e^{t/τ_N}, a positive total net growth rate $1/\tau_N$ generates CBMI's. By considering the fact that the net growth time τ_G is proportional to E/I_b from Eqs. (2) and (4), and the threshold beam current is determined when the τ_G is balanced with the τ_D, the threshold beam current I_{th} due to the CBMI for the same beam energy E can be calculated as

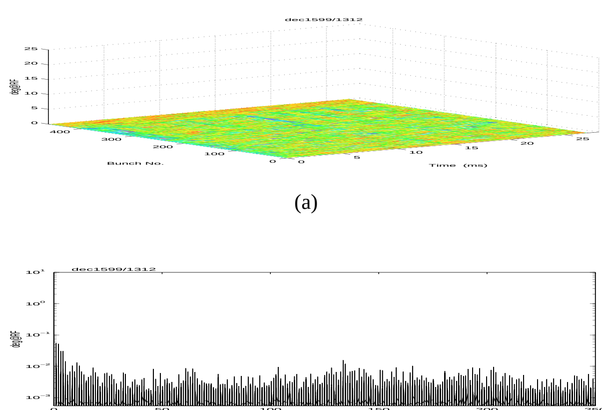
$$I_{th} = \frac{\tau_G}{\tau_D} \cdot I_o \, , \qquad (7)$$

where I_o is the beam current to calculate τ_G by the ZAP code or the beam current at which τ_G is measured. For the TM_{013} mode with $\tau_G = 9.22$ msec at $I_o = 100$ mA from ZAP code and $\tau_D = \tau_s = 7.84$ msec at 2.04 GeV from Eqs. (5) and (6), the calculated threshold beam current I_{th} of TM_{013} mode is about 117.6 mA at 2.04 GeV. LFS and Landau damping are not considered in this estimation.

3 COMMISSIONING RESULTS

3.1 Active Feedback Versus Energy Ramping

Since the growth rates of longitudinal CBMI's is a function of temperature of RF cavity, we have turned on the LFS at 2.04 GeV with the temperature tuned status. During the recent machine study period (December 15, 1999), we can damp all CBMI's at the beam current of 237.0 mA with the PLS LFS. By recording bunch phases in the dual port memories (DPMs) of the LFS, the time domain motions and the pseudo-spectrum for the 400 bunches when the LFS is turned on at 2.04 GeV are obtained to investigate the damping efficiency as shown in Fig. 1 (a) and (b) [4]. When the LFS is turned on at 2.04 GeV, all bunches oscil-



(a)

(b)

Figure 1: Time domain 400-bunch oscillations (a) and their pseudo-spectrum (b) when the LFS is turned on at 165.3 mA, 2.04 GeV. Four cavity temperatures are $37.8\,°$C, $47.3°$C, $45.7°$C, and $37.8°$C, respectively.

late in decoupled motions with small amplitudes less than 0.03 deg@RF, and the maximum amplitude of the pseudo-spectrum is less than 0.06 deg@RF. The measured amplitude reduction of sidebands which is obtained by a spectrum analyzer is about 70 dB. Therefore, all CBMI's are damped down to the noise level. Similar results can be obtained when the beam current is 237.0 mA.

These figures can be compared with Fig. 2 which is result of the 2.5 GeV operation where all conditions except the beam energy and the filling pattern are similar with those of Fig. 1. Though the synchrotron radiation damping time τ_s is decreased to 4.26 msec from 7.84 msec by ramping the beam energy to 2.5 GeV, a CBMI spectrum due to TM_{020} HOM is still strong. Since 468 bunches are oscillating with near 10 deg@RF amplitudes in time domain, and the maximum amplitude of the pseudo-spectrum is about 6 deg@RF, the damping of the active LFS at 2.04 GeV is more powerful than the synchrotron radiation damping at 2.5 GeV. We should cure the CBMI due to the TM_{020} HOM by the LFS or the HOM damper to supply users with the more stable beams at 2.5 GeV operation.

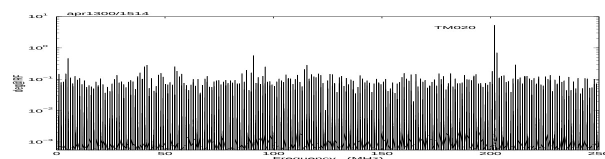


Figure 2: Pseudo-spectrum of 468 bunches (b) when the LFS is turned off at 161.9 mA, 2.5 GeV. Four cavity temperatures are $37.8°$C, $47.2°$C, $45.7°$C, and $38.1°$C, respectively.

3.2 Investigation of Transverse CBMI's

We have also detected the transverse CBMI's by using the LFS recording function during the injection as shown in Fig. 3 and summarized in Table 1 where f_{HOM} is the frequency of HOM, n is the coupled bunch mode number, and Q_o is the unloaded quality factor. By the help

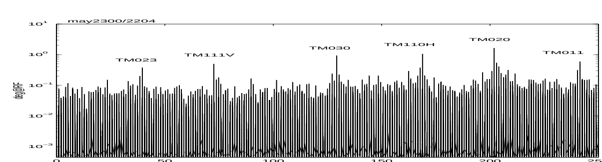


Figure 3: Pseudo-spectrum when LFS is turned off at 203.0 mA, 2.04 GeV. Four cavity temperatures are $40.8\,°$C, $46.8°$C, $45.6°$C, and $36.9°$C, respectively.

of the synchro-betatron coupling, transverse beam motions could be recorded by the LFS. The same transverse sidebands were also measured by a spectrum analyzer. Strong transverse CBMI's due to TM_{110}V, TM_{110}H and TM_{111}V HOM's are generated during the injection. But the sidebands of the transverse CBMI's and the instabilities in the transverse direction are reduced after the injection.

Table 1: Harmful HOM's of the PLS RF cavities.

f_{HOM} [MHz]	n	HOM	Q_o	Direction
758.6	241	TM_{011}	37,000	Longitudinal
1301.1	279	TM_{020}	112,000	Longitudinal
1707.0	194	TM_{013}	34,000	Longitudinal
1870.1	123	TM_{030}	34,000	Longitudinal
826.4	161	TM_{110}V	56,000	Vertical
833.7	158	TM_{110}H	56,000	Horizontal
1072.4	400	TM_{111}V	40,000	Horizontal

3.3 *Estimation of Feedback Damping Time*

To estimate the damping rate of the LFS and the threshold beam current when the LFS is turned on, we have performed the well known grow/damp process [4]. In this process, all CBMI's are initially damped by the LFS (normal feedback status) as shown in Fig. 1. Then, the normal feedback status is changed to the grow/damp process where an active damping process by the LFS will be followed after the natural growing process (after ∼13 msec). The evolution of two CBMI's with $n = 123$ and $n = 194$ due to the grow/damp process is shown in Fig. 4. Before

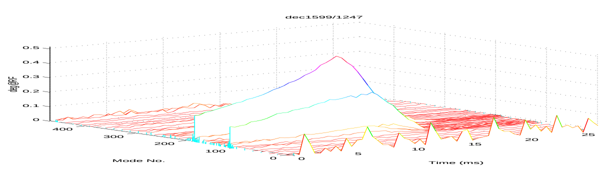


Figure 4: Evolution of two modal strengths in the frequency domain when the grow/damp process for 400 bunches is performed by the LFS at the beam current of 153.1 mA, 2.04 GeV. Temperature status is the same as that of Fig. 1.

a break point (∼13 msec), the net growth rate $1/\tau_N$ is $1/\tau_G - 1/\tau_s$ for each mode from Eqs. (3), (5), and (6). Therefore, we can estimate two total net growth rates by exponential fitting. The estimated pure growth time τ_G of $n = 123$ and $n = 194$ mode are 5.42 msec and 4.53 msec at 153.1 mA, respectively. Since we have ignored the Robinson damping effect and the Landau damping effect, true growth time of two CBMI's may be larger than these estimated values. After the break point, the net growth rate $1/\tau_N$ is $1/\tau_G - 1/\tau_s - 1/\tau_{fb}$ for each mode. We can estimate the damping rate of the LFS, $1/\tau_{fb}$ by subtracting the net growth rate for the after break point case from the net growth rate for the before break point case. The estimated damping time of the LFS, τ_{fb} for $n = 123$ and $n = 194$ mode are 2.07 msec and 2.34 msec, respectively. From Eqs. (5), (6) and (7), the estimated τ_G and $1/\tau_L \simeq 0$ for the current one-train bunch filling pattern, we can estimate the threshold beam currents for $n = 123$ and $n = 194$ modes as 506.7 mA and 385.6 mA, respectively.

3.4 *Source of the LFS Malfunction*

Recently, we have found that the LFS could not damp any CBMI's properly when the klystron for the RF cavity No. 1 has strong 36 Hz and its multiple noises, and the RF low level feedback systems for the cavity No. 1 and 3 have strong $3 \sim 5$ kHz and their multiple noises as shown in Fig. 5. When the klystron noises have large amplitudes, the large-amplitude modulations which are different from the synchrotron oscillation are generated, and thus, the synchrotron frequency is changed by the modulations. Therefore, the filter phase of the FIR algorithm becomes no more constant. When the noises from the RF low level systems are generated, the sidebands around the synchrotron frequency can be observed, and the small-amplitude modulations with the the noise frequencies are generated in the synchrotron oscillation.

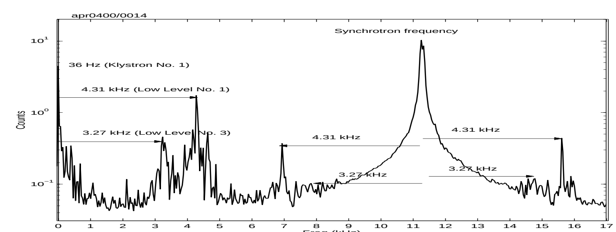


Figure 5: Beam signal spectrum at 236.6 mA, 2.04 GeV when two kind noises are generated simultaneously.

4 SUMMARY

We can completely damp all longitudinal CBMI's at 237.0 mA, 2.04 GeV and obtained brighter and stable beam at the beamline by turning the LFS on. The estimated threshold beam current which can be obtained by the LFS is about 400.0 mA. But, due to the RF phase modulations of the RF noises, we can not increase the beam current further. We are investigating the noise sources to remove the modulation, and also investigating a new filter algorithm such as the IIR filter. After removing the modulation, we will retry to increase threshold beam current further by the PLS LFS.

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