EFFECT OF BANDWIDTH OF LOW LEVEL RADIO FREQUENCY SYSTEM ON THE INSTABILITY OF ELECTRON BEAM

Zong-Kai Liu#, Lung-Hai Chang, Mei-Hsia Chang, Ling-Jhen Chen, Po-Yuan Chen, Fu-Tsai Chung, Ming-Chyuan Lin, Chih-Hung Lo, Chi-Lin Tsai, Ming-Hsun Tsai, Chaoen Wang, Meng-Shu Yeh, Tsung-Chi Yu, NSRRC, Hsinchu, Taiwan

Abstract

The analog Low Level Radio Frequency (LLRF) system is used at Taiwan Photon Source (TPS) RF system. It is composed of three feedback loops to control the amplitude and phase of accelerating field and the frequency of RF cavity. Instability of electron beam and accelerating field due to the bandwidth of LLRF system were observed during the TPS commissioning. This effect was studied and the results would be presented in this paper.

INTRODUCTION

Taiwan Photon Source (TPS) is a modern light source with 3 GeV electron energy located in NSRRC, Taiwan [1]. There were two phases for the TPS commissioning. The phase I commissioning, which was done in the end of March 2015 with maximum stored beam current of 100 mA, was operated with 5-cells Petra cavities and without insertion devices. The phase II commissioning started in the third quarter of 2015 with two superconducting RF (SRF) cavities and 10 sets of insertion devices.

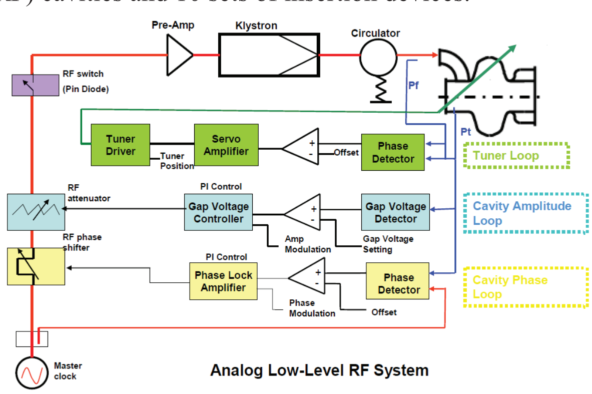

Figure 1: The block diagram for the LLRF system.

The analog Low Level Radio Frequency (LLRF) system is used at TPS RF system. It is composed of three feedback loops to control the amplitude and phase of accelerating field and the frequency of RF cavity. Figure 1 shows the block diagram for the LLRF system of TPS. The initial designed bandwidth of the gap voltage controller of the amplitude loop is about 7.2 kHz. With this bandwidth, the instability of electron beam at about 20 mA was observed during phase I commissioning with two Petra cavities operated at 1200 kV. The maximum stored beam current could not exceed about 25 mA. After reducing the bandwidth of amplitude loop to 720 Hz, the longitudinal instability was observed at about 80 mA and the stored beam current could reach designed goal of 100 mA [2]. For the phase II commissioning, the bandwidth of the gap voltage controller was further reduced to 596 Hz, and the stored beam current reached 520 mA at the end of December 2015 with two SRF cavity operated at 1400 kV. However, the beam processing was needed for the RF coupler every week due to the heavy gas loading [3]. During the beam processing, the beam current was fixed at certain level and then the gap voltage was decreased. The instability of LLRF system was observed during beam processing.

A small signal model for the beam-cavity interaction with feedback loop [4] was used to analyse the effect of bandwidth of LLRF system on the instability of RF system. The model and the results are presented in the following sections.

PEDERSEN MODEL

The Pedersen model with feedback loops was used to simulate the instability of RF system for a given steady state condition, as shown in Fig 2. It describes the transmissions from small modulations of beam current and generator current to the cavity voltage, for both amplitude and phase. Due to the slow response of tuner loop, only amplitude and phase loop were considered in the simulation.

Transfer Functions in the Pedersen Model

The transfer functions from the total current to the cavity voltage are given by [4]:

$$G_{pp}(s) = G_{aa}(s) = \frac{1}{2}\{\frac{Z(s+j\omega_{RF})}{Z(j\omega_{RF})} + \frac{Z(s-j\omega_{RF})}{Z(-j\omega_{RF})}\} \quad (1)$$

$$G_{pa}(s) = -G_{ap}(s) = \frac{j}{2}\{\frac{Z(s+j\omega_{RF})}{Z(j\omega_{RF})} - \frac{Z(s-j\omega_{RF})}{Z(-j\omega_{RF})}\} \quad (2)$$

where Gpp(s) and Gaa(s) are phase to phase and amplitude to amplitude transfer functions, and Gpa(s) and Gap(s) are phase to amplitude and amplitude to phase transfer functions. The Z(s) is the cavity impedance, which is given by:

$$Z(s) = \frac{2\sigma \cdot sR_S}{s^2 + 2\sigma \cdot s + \omega_{CAV}^2} \cdot \frac{1}{1+\beta} \quad (3)$$

where the ω_{CAV} is the cavity resonant frequency, and σ is defined as:

$$\sigma \equiv \frac{\omega_{CAV}}{2Q_L} \quad (4)$$

where Q_L is the loaded quality factor of the cavity. The final transfer functions from the beam current to the

#liu.zk@nsrrc.org.tw

cavity voltage are obtained by projections of the current components on the total current:

$$G_{aa}^{b} = G_{pp}^{b} = G_{pp}\frac{I_B}{I_T}\cos(\angle\vec{I}_B - \angle\vec{I}_T) + G_{pa}\frac{I_B}{I_T}\sin(\angle\vec{I}_B - \angle\vec{I}_T) \quad (5)$$

$$G_{ap}^{b} = -G_{pa}^{b} = G_{ap}\frac{I_B}{I_T}\cos(\angle\vec{I}_B - \angle\vec{I}_T) + G_{pp}\frac{I_B}{I_T}\sin(\angle\vec{I}_B - \angle\vec{I}_T) \quad (6)$$

The relations for the generator current component are similar.

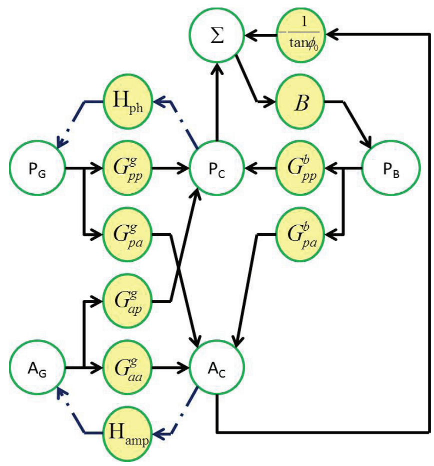

Figure 2: Pedersen model with amplitude and phase feedback loops.

The beam transfer function which can be written as:

$$B = \frac{\Omega_S^2}{s^2 + \alpha_S \cdot s + \Omega_S^2} \quad (7)$$

where the α_S is the damping term and Ω_S is the synchrotron oscillation frequency.

Table 1: RF Parameters

Style	Phase I	Phase II
f_{RF}	499.65 MHz	499.65 MHz
Q_L	7,800	6.6E4
Q_0	29,000	1.8E9
R_S	14.5 MΩ	8.55E10 Ω
α	2.4E-4	2.4E-4
U0	853 keV	853 keV
E	3 GeV	3 GeV
h	864	864

Transfer Functions of Feedback Loops

The block diagram for the LLRF system of TPS is shown in Fig 1. The transfer functions of amplitude and phase loop can be written as:

$$H_{amp} = \frac{\Delta I_G / I_G}{\Delta V_C / V_C} = \frac{\Delta I_G}{\Delta P_f}\frac{\Delta P_f}{\Delta V_{con}}\frac{\Delta V_{con}}{\Delta V_{in}}\frac{\Delta V_{in}}{\Delta V_C}\frac{V_C}{I_G} \quad (8)$$

$$H_{ph} = \frac{\Delta\phi_G}{\Delta\phi_C} \quad (9)$$

The P_f is the forward power of cavity, V_{con} is the control voltage of controller and V_{in} is the input voltage of controller. For the simplicity, the transfer functions of both loops were approximated to a first order transfer function with a delay time as follow:

$$H = \frac{gain \cdot bandwidth}{s + bandwidth} \cdot \exp(-s \cdot T_{Delay}) \quad (10)$$

The dominate bandwidth of the feedback loop is from the controller, therefore the bandwidth could be calculated form the circuit model of the controller. The DC gain of the feedback loop can be obtained from eq. (8), (9) and the data of power measurement and the voltage calibration. The delay time is assumed to be 10 μsec. The RF parameters for the Petra cavity and SRF are shown in the Table 1.

SIMULATION RESULTS

Simulations were made by using the MATLAB package. The stability was determined by the real part of the poles of the close loop system. If all of the real part of the poles were negative, the system is stable. For the given gap voltage, the maximum stable stored beam current can be obtained. With 7.2 kHz of the bandwidth of amplitude loop, the system became unstable at 19 mA and 13 mA at gap voltage of 1200 kV and 900 kV, respectively. The observed maximum stored beam current with 7.2 kHz bandwidth of amplitude loop during phase I commissioning were about 25mA and 18 mA for 1200 kV and 900 kV, respectively. This is due to that the injection efficiency is still larger than the beam lost rate even though the system is already in the unstable condition. Similar phenomenon is also shown in the case of 720 Hz of LLRF system bandwidth. The system becomes unstable at about 88 mA, however, the observed maximum beam current could be exceed 100 mA.

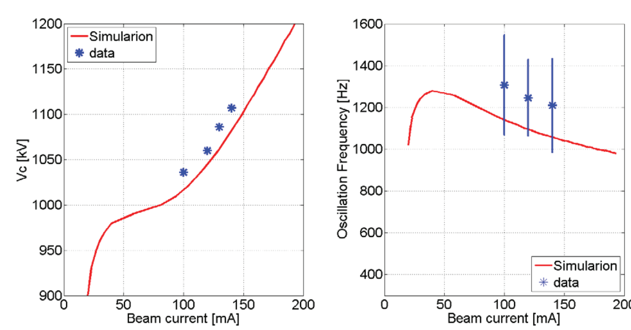

Figure 3: Minimum stable gap voltage [LEFT] and the oscillation frequency [RIGHT] as function of beam current.

Figure 3 shows the results of minimum stable gap voltage for the given beam current, as well as the oscillation frequency of the gap voltage at the time of oscillation started, for the beam processing during phase II commissioning. During the beam processing at about 150 mA, the gap voltage was lower than the usual operation with only one cavity, typically should be lower than 1000 kV. With the 596 Hz of LLRF system bandwidth, the observed minimum stable gap voltages for 100 mA to 140 mA are also shown in the Fig 3. The difference between observation and simulation may be

ISBN 978-3-95450-147-2

from the simplified model and the uncertainty of voltage measurements. The gap voltage would start oscillated with a specific oscillation frequency if the gap voltage was lower than the minimum stable gap voltage. The simulation prediction of the oscillation frequency is lower than the observation, but still within the uncertainty.

DISCUSSION

The Bode plots were used to study the instability of the RF system with the beam current stored. One can calculate the effective transfer function of Ag to Ac in the small signal model without the amplitude and phase feedback loop, and plots the open loop response with the amplitude feedback with different bandwidth, as shown in the Fig 4.

Because of the rapidly drop of the phase near the synchrotron frequency, the phase always reaches -180 degree near synchrotron frequency even without the feedback loop. Large bandwidth of amplitude loop has large magnitude at high frequency, especially near the synchrotron frequency. Therefore the gain margin of the open loop transfer function with the feedback loop would decrease when the bandwidth of amplitude loop increases. The system becomes unstable when the gain margin smaller than zero, therefore the maximum stored beam current would decrease with the increasing of bandwidth of amplitude loop.

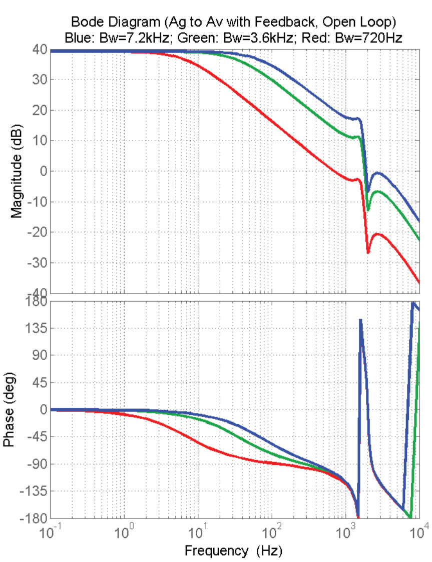

Figure 4: The bode plots for the open loop response with the amplitude loop.

The effect of bandwidth of both amplitude and phase loops on the maximum stored beam current are shown in the Fig. 5. The limitation of maximum stored beam current is mainly from the bandwidth of amplitude loop. If the bandwidth of amplitude loop was small enough compare to the synchrotron frequency, the bandwidth of phase loop almost have no effect on the maximum stored beam current. Once the bandwidth of amplitude loop is close to the synchrotron frequency, the maximum stored beam current drops rapidly.

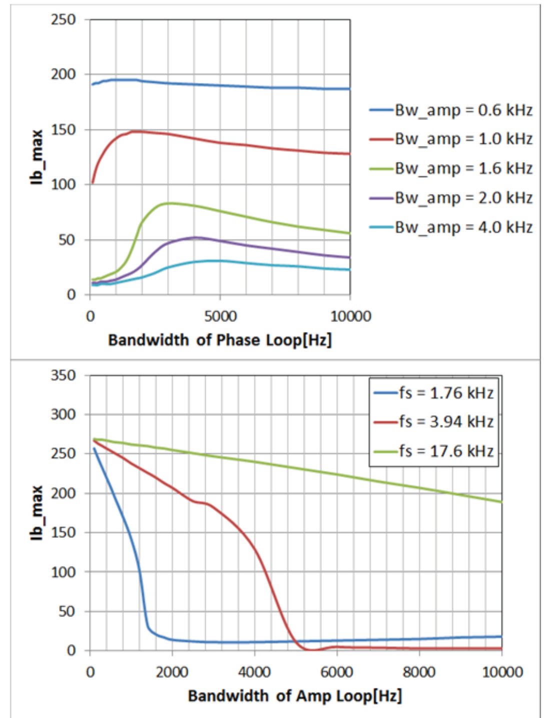

Figure 5: The maximum stored beam current as function of bandwidth for the amplitude loop [TOP] and the phase loop [BOTTOM].

CONCLUSION

The analog LLRF system is used at TPS RF system. During the TPS commissioning, instability of electron beam and accelerating field due to the bandwidth of LLRF system were observed. A small signal model for the beam-cavity interaction with feedback loop was used to analyse the effect of bandwidth of LLRF system on the instability of RF system. The simulated results were consistent with the observations. The gain margin of the open loop transfer function with the feedback loop would decrease when the bandwidth of amplitude loop increases, so as to decrease the maximum stored beam current. Therefor to avoid such instability, the bandwidth of the LLRF system should be much lower than the synchrotron frequency.

REFERENCES

[1] C.C. Kuo et al., "Design Status of Taiwan Photon Source", EPAC'08, Genoa, June 2008, (2008).
[2] C.C. Kuo et al., "Commissioning of the Taiwan Photon Source (TPS)", IPAC'15, Richmond, May 2015.
[3] Ch. Wang et al., "Beam Processing for High Current SRF Operation for Light Sources", these proceedings, IPAC'16, Busan, Korea (2016).
[4] F. Pedersen, "Beam Loading Effects in the CERN PS Booster", IEEE Transactions on Nuclear Science, Volume 22, Issue 3, p. 1906-1909 (1975).