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NEW RF FEEDBACK SYSTEM AND SIMULATIONS FOR SUPPRESSION OF COUPLED-BUNCH INSTABILITIES AT SuperKEKB

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Abstract

SuperKEKB is an asymmetric electron-positron circular collider based on nano-beam scheme at interaction region and large beam current. Longitudinal coupled-bunch instabilities (CBI) near RF frequency modes become bigger as the beam current increase. We developed new CBI damper to suppress newly arisen CBI modes (μ = -1, -2, -3) in SuperKEKB. The new damper will install in Low Level RF control system. LLRF control system was digitalized; it is a FPGA- based system on the microTCA for the high beam current operation of SuperKEKB. New CBI damper is independent of main LLRF control components. In test-bench measurements, our new CBI damper performed very well and satisfied required specifications. For SuperKEKB Phase-2 commissioning from January 2018, we calculated simple feedback model to estimate feedback loop gain of the new CBI damper.

INTRODUCTION

SuperKEKB is a high-luminosity asymmetric electron-positron collider upgraded from KEKB. The SuperKEKB Phase-1 commissioning was operated from February to June in 2016, and the Phase-2 will be carried out from January in 2018. Table 1 provides the main parameters of SuperKEKB [1] for this study. The SuperKEKB storage ring consists of a 7 GeV high-energy ring (HER) for electrons and a 4 GeV low-energy ring (LER) for positrons. One of the major differences between SuperKEKB and KEKB is increase of the beam current. In SuperKEKB design, longitudinal coupled-bunch instabilities (CBI) from the interaction between the beam and the accelerating mode of cavity will be serious, and there is every possibility of higher modes ($\mu = -2$ and -3) destabilized. So we need new mode-feedback system to counteract these multi-bunch oscillations.

Table 1: SuperKEKB and Cavity Parameter

parameters for SuperKEKB	value LER	value HER
Energy: E	4.0 GeV	7.0 GeV
Beam current: I_0	3.6 A	2.62 A
Mom. compact.: α_c	3.25×10^{-4}	4.55×10^{-4}
Synch. freq.: f_s	2.43 kHz	2.78 kHz
Harmonic number: h	5120	
RF frequency: f_{rf}	508.877 MHz	
$f_0 = f_{rf}/h$	99.39 kHz	
Number of cavity	22	ARES 8, SC 8
for Cavity	**ARES**	**SC**
$V_c/cavity$	0.5 MV	1.5 MV
R_s/Q_0	15 Ω	93 Ω
Q_0	1.1×10^5	2.0×10^9
coupling factor: β	5.0	4.0×10^4

In the KEKB operation, the lowest mode of CBI called μ = -1 mode had been excited, and we suppressed it by using the CBI damper, which corresponds to only μ = -1 mode [2]. While upgrading to SuperKEKB, we predict that μ = -1, -2 mode instabilities will be excited at design beam current (LER: 3.6 A, HER: 2.6 A). To reach SuperKEKB design current, $\mu = -2$ mode will occur and $\mu = -1$ mode will become more serious (Figure 1). So we developed a new CBI damper as an RF feedback (FB) component [3]. We expect that CBI $\mu = -1, -2, -3$ mode will be suppressed by using this new damper in SuperKEKB operation.

COUPLED-BUNCH INSTABILITIES CAUSED BY ACCELERATING MODE

We reuse the KEKB RF system [4], which has two cavity types. One is a normal conducting (NC), and the other is superconducting (SC). In HER, a NC and SC cavity are used, and in LER, only NC cavity. The NC cavity is a unique cavity of KEKB and SuperKEKB called "ARES" [5]. ARES has a three-cavity structure: an accelerating cavity is coupled with an energy storage cavity via a coupling cavity in order to reduce cavity-detuning by beam loading [5]. The reason why CBI caused by accelerating mode become serious is that cavity detuning amount become larger as the beam current increases (following equation). $\Delta f = -(I_0 \sin\phi_s/2V_c)\cdot(R_{sh}/Q_0)\cdot f_{rf}$, where I_0 is beam current, ϕ_s is synchronous phase, V_c is accelerating voltage, R_{sh} is shunt impedance, Q_0 is unloaded quality factor, and f_{rf} is accelerating frequency.

To evaluate power of CBI, we use growth rate which is well known in Equation (1).

$$\tau_\mu^{-1} = AI_0 \sum_{p=0}^{\infty}\{f_p^{(\mu+)}\mathrm{Re}Z^{||}(f_p^{(\mu+)}) - f_p^{(\mu-)}\mathrm{Re}Z^{||}(f_p^{(\mu-)})\} \tag{1}$$

$$f_p^{(\mu+)} = (pM+\mu)f_0 + f_s, \quad f_p^{(\mu-)} = \{(p+1)M-\mu\}f_0 - f_s$$
$$f_{rf} = hf_0 \quad ,$$

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where τ_μ^{-1} is growth rate, $Z^{||}$ is longitudinal impedance, f_s is synchrotron frequency, and h is harmonic number. Detuning impedance condition was applied to resonance frequency of $Z^{||}$. Figure 1 shows calculations of growth-rate for CBI modes caused by accelerating mode (Top : LER, Bottom : HER). As we calculated this Radiation Damping Rate, wiggler magnets are set to work maximum of SuperKEKB design.

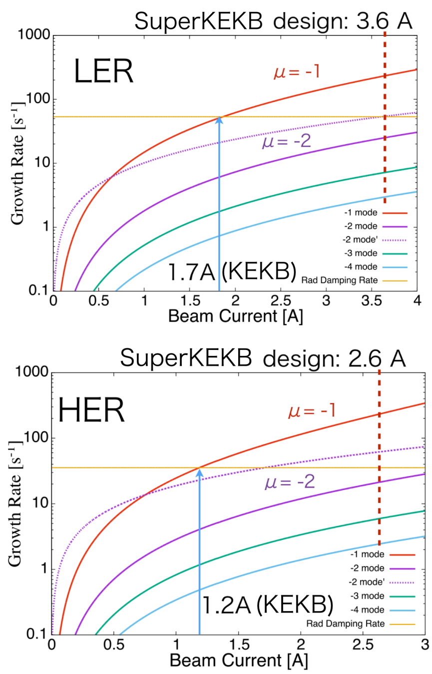

Figure 1: Growth rate by beam current. Dotted curve indicates μ = -2 mode in the case of a cavity parked with 150-kHz detuning.

RF FB SYSTEM FOR CBI DAMPER

Low level RF (LLRF) control system is newly developed in digital for large beam current in the SuperKEKB operation [6]. New system is performed by FPGA boards worked on microTCA platform. Main functions are Vc FB control, cavity tuner control, and RF level detectors for interlock as shown Figure 2. At SuperKEKB Phase-1 commissioning, this new LLRF control systems worked well without serious trouble.

Figure 3 shows a block diagram of a RF FB system for CBI damper (mode feedback). CBI damper signals are combined to Vc FB control signals. Figure 4 shows a block diagram of new CBI damper. The CBI damper consists of single-side band filter (SSBF) which is analog circuit and digital bandpass filter (BPF) which is made on FPGA board (KC705, Xilinx) [3]. The fundamental method of this system is based on the KEKB damper. First step of CBI damper, only lower sideband of transmit signals can be passed through SSBF. RF are input as reference signals for up/down conversion. This SSBF was improved, and it has very good characteristics [3]. Second step, only frequency of CBI modes are transmitted, which is attained by using digital BPF (Fig. 4 bottom). To suppress CBI $\mu = -1, -2, -3$ modes at the same path of a RF system, one SSBF and three digital BPFs are combined in parallel (Fig. 4 top). Since the BPF can be adjusted the phase independently for each CBI mode, feedback signals are optimized conforming with the phase frequency characteristics of several components in entire RF system. The control parameters of the digital BPF can be given remotely by EPICS records.

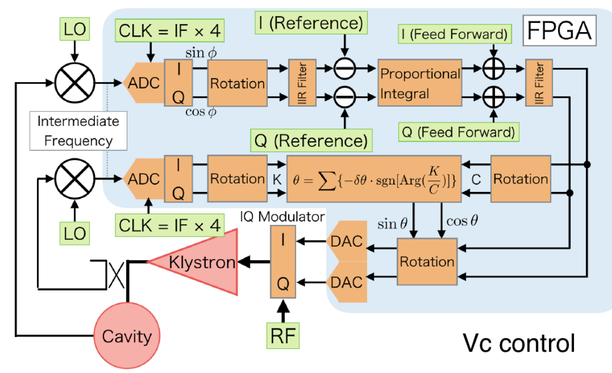

Figure 2: Block diagram of the digital Vc FB control system.

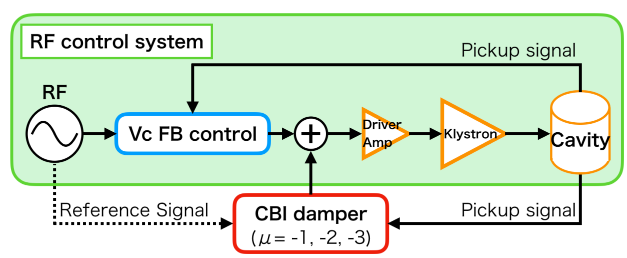

Figure 3: Block diagram of an RF FB system for CBI damper.

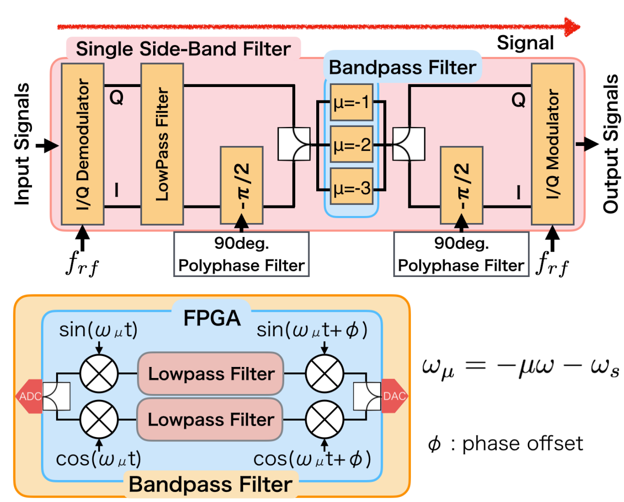

Figure 4: Block diagram of a new CBI damper.

Before practical use at beam commissioning, we have to make sure of CBI damper performance. The nucleus of

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this damping instabilities method is attenuation of apparent impedance only at frequency that excites CBI. Figure 5 shows the test-bench measurement of impedance damping with a simulant cavity(Q = 9000). The impedance is reduced in accordance with the set loop gain and parameters of digital BPF (e.g. passband frequency of several filters). It found that CBI damper performs following our expectation. At SuperKEKB Phase-2 commissioning, we will try to suppress beam oscillations by using new CBI damper.

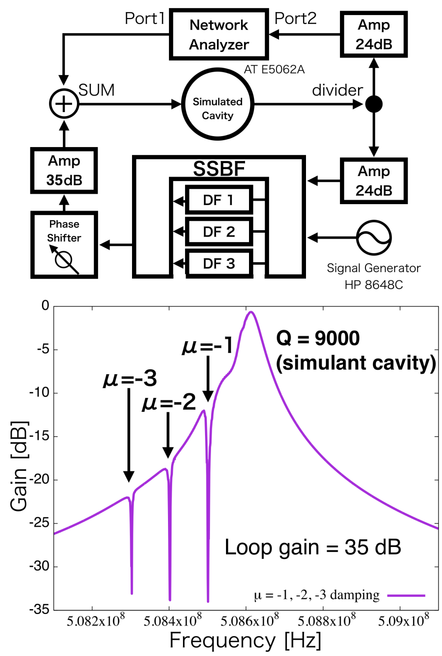

Figure 5: Block diagram for the FB loop evaluation (Top), and the damping characteristics for the FB loop (Bottom).

ESTIMATION OF THE DAMPING EFFECT

Looking ahead to SuperKEKB operation, we calculated RF FB to suppress multi-bunch oscillations. Because the number of CBI damper applied to cavities cannot be identified without evaluation of loop gain. The main idea of CBI damping simulation is that bunches are kicked by wake fields and FB RF fields at cavities. The CBI is an instability caused by the interaction between the impedance of the entire accelerator and the multi-bunch beam. If CBI dampers are applied to all RF stations of storage ring, it is enough to supply the damping effect over the entire circumference of the ring. However it is necessary to suppress CBI with the installation of CBI dampers as few units as possible (for example, it is hard to install in stations of SC cavity because SC is more sensitive than NC). This simulation is evaluation of the effect of difference of the number of RF stations which CBI damper is applied to. The relation between pickup signals and wake fields level in a cavity is estimated from SuperKEKB Phase-1 commissioning measurement. Figure 6 shows estimation of the effectiveness of CBI damping in beam-current change for the difference of the number of the CBI damper applied to each RF station for LER (CBI dampers and RF stations have a one-to-one relationship). In this figure, horizontal axis denotes beam current, and vertical axis is amplitude ratio of bunch oscillations to zero-current condition. Initial gain of pickup signal is fixed to +60dB (since intensity of pickup signals was so weak). The gain control system may be required, so we plan to consider a new system including it after Phase-2 commissioning. As an estimation result, it was found to need some CBI dampers for reach SuperKEKB design beam current.

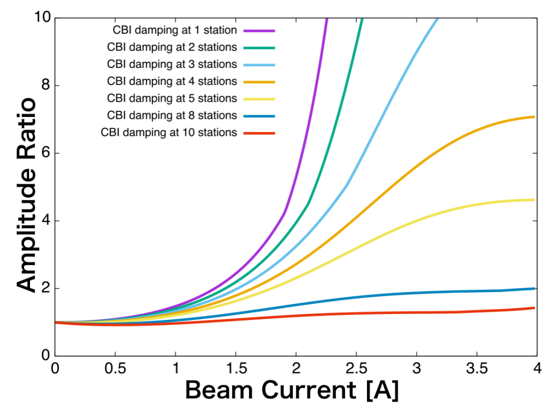

Figure 6: Estimation of the effectiveness of CBI damping for the different numbers of the CBI dampers applied to each RF station.

CONCLUSION

Developed new CBI damper performance satisfies our required specifications [3]. SSBF and digital BPF was improved and their characteristics is very well. In calculation of CBI growth-rate (especially $\mu = -1$ mode), amplitude of bunch oscillation with beam current increase depends strongly on the number of the dampers applied. It is found that we need CBI dampers more than one, but we still have not clarified the exact number of dampers required. In SuperKEKB Phase-2 commissioning, we expect that CBI can suppress by new CBI damper, and we will define how many dampers should be applied for the design beam current.

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