Beam Test of a Direct RF Feedback System for KEKB

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Abstract

This paper describes high beam current experiments of a direct RF feedback (DRFB) system conducted in TRISTAN AR. The DRFB was operated with a prototype superconducting cavity for KEKB. It was observed that the DRFB greately improved stability of the RF system under an extremely heavy beam loading. For example, coherent synchrotron oscillation was suppressed and the phase margin for the stability limit was increased. Total stored current could be increased up to 573mA and the high current beam was stably stored with the DRFB on.

1 Introduction

The KEKB, an asymmetric electron-positron collider, will be operated with a beam current of several amperes. The ARES normal conducting cavities [1] and superconducting cavities (SCC) [2] will be used in KEKB. Longitudinal coupled-bunch instabilities of modes μ=-1,-2, etc., (μ is the coupled-bunch number) caused by detuning to compensate for the reactive component of the beam loading will be sufficiently suppressed, indebted to large stored energy in the ARES and SCC.

Even with the ARES and SCC, however, the beam-loading is so heavy that it can degrade the stability of the operating RF (essentially μ=0) mode. For example, following problems are expected: (1) phase margin is small for the static Robinson stability criterion, (2) the Automatic Level Control (ALC) and Phase Lock Loop (PLL) become unstable due to cross-talk between them, and (3) insufficient transient controllability on the occation of one station trip, beam dump, or others. In order to solve these problems, it is planned to equip the RF control system with a direct RF feedback loop (DRFB), in addition to the usual ALC and PLL loops.

The principle of the DRFB is to monitor the cavity voltage seen by the beam and reinject it into the cavity. Then the impedance of a cavity seen by the beam and by driving RF signal is considerably reduced [3]. In the CERN SPS, during high intensity proton cycle the DRFB was used to reduce the impedance of a SCC to avoid beam instabilities. The cavity voltage was made negligibly small even in the presence of the strong proton beam current (0.2A) [4].

In 1996, a series of high beam current experiments for KEKB was conducted in TRISTAN Accumulation Ring (AR) to test the ARES and SCC with a high current beam up to 0.5A [5]. In the experiment, the DRFB was installed in the RF control system for the SCC. The performance and the effect of DRFB on stabilizing the operating RF mode were investigated. The results are presented in this paper.

2 Experimental Set Up

The AR had been operated as the injector of the TRISTAN Main Ring and as a SOR machine: at that time 4 units of 11-cell APS type cavities were used. Prior to the experiment, these APS cavities were removed temporarily and one SCC and two sets of ARES cavities were installed. During the experiment of the DRFB, only the SCC was operated and the ARES's were detuned. The SCC used for the experiment is a single-cell damped cavity. All monopole and dipole HOMs are extracted through the beam pipes with large diameters and absorbed by ferrite dampers. Table 1 shows main machine parameters of the AR for the experiment in parallel with parameters of the accelerating mode of the SCC. Details of the SCC, together with beam test results of cavity performances, are reported elsewhere [6] [7].

Table 1
Main parameters of the AR and SCC

(AR)	
Particles	electrons
Beam Energy E_b	2.5 GeV
Beam Current I_b	573 mA (max)
RF frequency f_{RF}	508.58 MHz
Harmonic number	640
Radiation loss/turn U_0	0.146 MeV
Radiation damping time τ_e	21 msec
RF voltage by SCC V_c	0.6~ 2.5 MV
(SCC)	
R/Q	93 Ω
Loaded-Q Q_L	8.9×10^4

Fig. 1 shows a schematic view of the RF system. The DRFB loop is formed by combining the pick-up signal with the main driving RF signal. The phase and amplitude of the feedback signal with respect to the driving RF are monitored and appropriately adjusted. There is an additional phase lock loop in the DRFB line, which compensates for a possible slow phase drift in the RF amplifier and the modulator. The bandwidth of this loop is limited to very low frequency by the LPF in order not to affect the response of the DRFB loop. Other conventional feedback loops employed are: the ALC and PLL loops to control the cavity voltage, another PLL to compensate for a phase change around the klystron, and a tuning control loop to adjust the resonant frequency of the cavity.

3 Stability Limit with DRFB

Fig. 2 shows a block diagram of the DRFB loop. We discuss here the effect of the DRFB on the stability for a very simplified case where delay around the loop is neglected (τ=0) and G is represented as K/R (K is

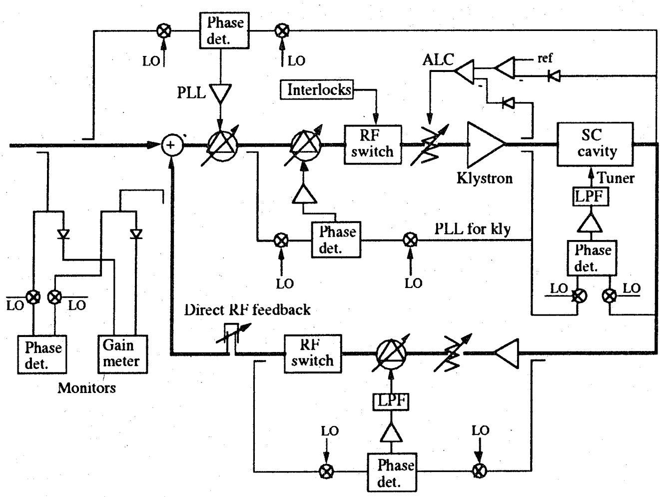

Fig. 1 Schematic view of the RF control system for SCC.

a real number and R is the shunt impedance). It is also assumed that $\omega_{sc}T_f \ll 1$, where ω_{sc} and T_f are the coherent synchrotron frequency and the filling time of the cavity, respectively. In this case we obtain a phasor diagram shown in Fig. 3. It is seen that the static Robinson stability limit corresponds to $\phi_L' - \phi_z' = \phi_s$, which leads to $\sin\phi_s + Y_{max}' \sin 2\phi_z'/2 = 0$. ($Y'$ and Y are defined as $I_b/I_T' \cos\phi_z'$ and $I_b/I_T \cos\phi_z$, respectively.) Since G is a real number, $Y' = Y/(1+K)$ and $\tan\phi_z' = \tan\phi_z/(1+K)$. From these relations we obtain,

$$\sin\phi_s + \frac{Y_{max}\ \tan\phi_z}{(1+K)^2 + \tan^2\phi_z} = 0. \tag{1}$$

(If we set $K = 0$, eq. 1 gives the well-known equation of $\sin\phi_s + Y_{max}\ \sin 2\phi_z/2 = 0$ without the DRFB.) By combining eq. 1 with a relation of

$$\tan\phi_z = \tan\phi_L + Y(\tan\phi_L \cos\phi_s - \sin\phi_s), \tag{2}$$

which is obtained from the vectors, Y_{max} can finally be represented as a function of ϕ_L, ϕ_s and K.

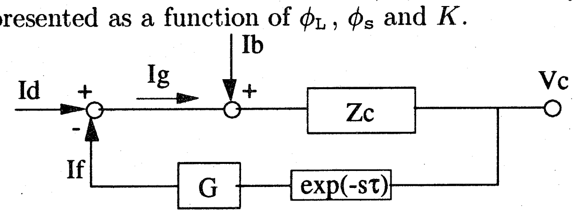

Fig. 2 Block diagram of the direct RF feedback loop.

As an example, Fig. 4 shows the Y_{max} as a function of ϕ_L for the cases $K = 0$ (no DRFB), $K = 1$ and $K = 2$ for $\phi_s = 75°$. It also shows a curve of $\phi_z = 0$, which gives another limit concerning the dynamic stability condition. The area between the two lines is a stable region. It is seen clearly that the DRFB increases this area. For an actual system, the delay, an exact form of G, and other loops such as ALC and PLL should be taken into account. Nevertheless, this simple model is useful to help intuitively understand the system.

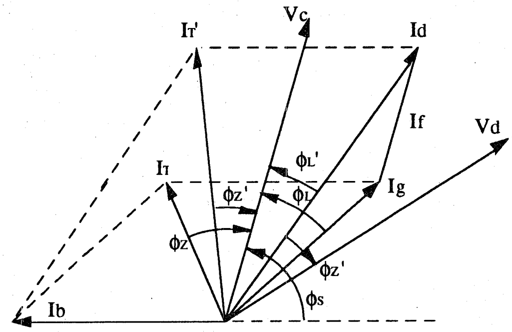

Fig. 3 Phasor diagram of the system.

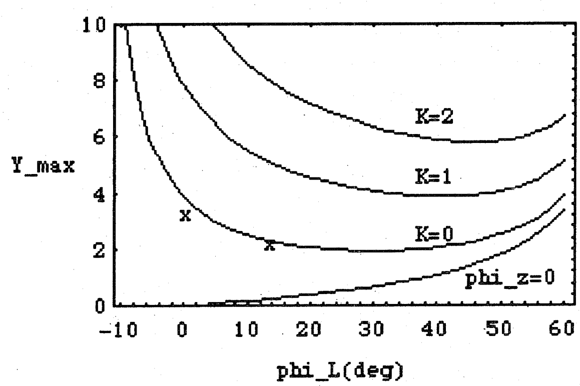

Fig. 4 Calculated stability limit for the simplified model. Observed beam losses without the DRFB are marked by ×.

4 Beam Test Results

Most of the DRFB experiment was conducted at a total beam current of 400mA in 16 bunches and the cavity voltage of 1.0 ~ 1.5MV. The loop gain was set as $K = 2 \sim 4$. Without the DRFB, we observed a strong coherent synchrotron oscillation of mode μ=0, in spite of a relatively large loading angle ($\phi_L = -15°$) introduced to increase the margin for the stability. The amplitude of the cavity phase oscillation was fluctuating, as an envelope of the oscillation is shown in Fig. 5a. When the oscillation was blown up, the amplitude reached as high as 1.4° of the RF signal (Fig. 5b). With the DRFB on, the oscillation was sufficiently suppressed down to less than 0.2° (Fig. 5c). Fig. 6 shows spectra of the pick-up signal observed by a spectrum analyzer. The synchrotron side bands are reduced by 10 dB with the DRFB on.

Next we studied the effect of the DRFB on the phase margin. A beam of 400mA was stored at V_c=1.5MV (Y=2.2) and $\phi_L = -15°$. Then the ϕ_L was increased slowly until the beam was lost due to the coherent oscillation. Without the DRFB, the beam was lost at $\phi_L = +14°$. With the DRFB on, the beam could be kept up to $\phi_L = +23.3°$. This study was done also at V_c=1.0MV (Y=3.3). The beam was lost at $\phi_L = +0.5°$ without, and at $\phi_L = +8.4°$ with the DRFB on, respectively. Thus the phase margin was largely increased with the DRFB. If we compare the results with the calculated

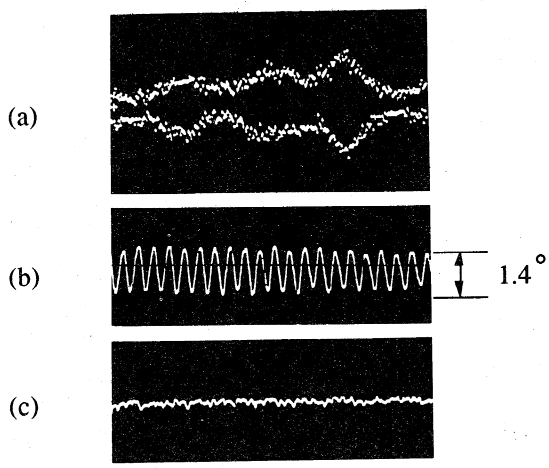

Fig. 5 Phase of the cavity voltage: (a) an envelope and (b) the maximum amplitude without the DRFB, and (c) with the DRFB on.

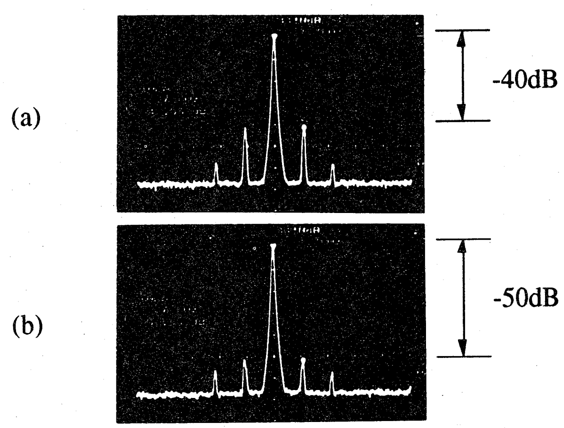

Fig. 6 Spectra of the pick-up signal: (a) without and (b) with the DRFB.

limit shown in Fig. 4, there is a fairly good agreement for the cases of no DRFB. With the DRFB, however, the beam loss occurred at smaller ϕ_L than the calculated values: this might be attributed to the loop delay or the cross talk between the ALC and PLL. Further analysis including the delay is in progress.

Frequency response of the closed loops of the ALC and PLL with a beam was measured using a FFT dynamic signal analyzer. Without the DRFB, a sharp peak appeared at 21 kHz corresponding to the synchrotron frequency (Fig. 7a), which leads to an excitation of the oscillation. With the DRFB on, the peak was eliminated (Fig. 7b). This means that the DRFB prevents the oscillation from being excited by the ALC and PLL loops.

Finally, the maximum stored current could be increased with the DRFB. On the last day of the experiment, we tried to increase the beam current as high as possible. After several times of beam loss around 500mA due to the coherent oscillation without the DRFB, we switched the DRFB on. Then the current was successfully increased up to 573mA and stably stored. We had no beam loss due to the instability with the DRFB on. This current limitation (573mA) was not by the instability, nor by cavity performances, but by a saturation due to a ballance between the beam life time and the injection rate.

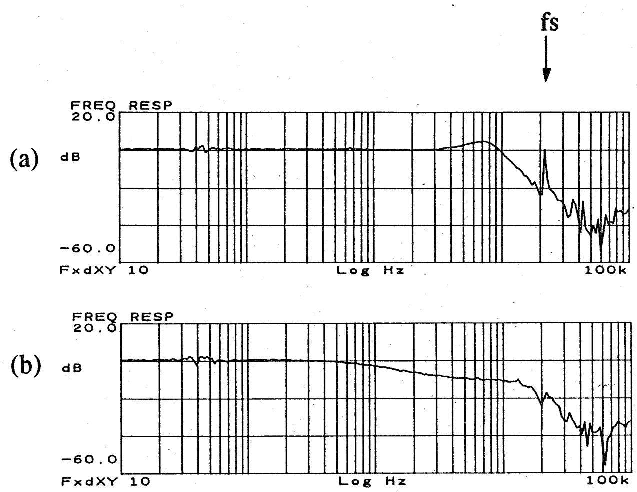

Fig. 7 Frequency response of the closed loop of the PLL: (a) without and (b) with the DRFB.

5 Conclusion

The DRFB was tested in the AR with a high current beam of 0.5A. It effectively suppressed the coherent synchrotron oscillation and increased the phase margin. The stability of the system was greatly improved and thus the stored current could be increased. It was demonstrated that the DRFB plays an important roll in the KEKB RF system.

Acknowledgement

The authors would like to thank the members of KEKB superconducting cavity group for their support in the experiment. We also thank Dr. Y. Funakoshi for the helpful operation.

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